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Review of the advances in open-cycle absorption air-conditioning systems

Napoleon Enteria [a,b,*], Hiroshi Yoshino [b], Akashi Mochida [b]

[a] Enteria Grün Energietechnik, Davao 8000, Philippines
[b] Faculty of Engineering, Tohoku University, Sendai 980-8579, Japan

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ABSTRACT

A large percentage of building energy consumption is for the maintenance of indoor thermal comfort conditions in different climatic conditions, particularly in hot and humid climates. Typical heating, ventilating and air-conditioning systems present an expensive source of energy or electric energy consumption. However, these processes have possible alternatives, materials and energy sources that are more economical and environmental friendly to support the building's indoor thermal environment. The application of hydrophilic liquid desiccant materials or absorbents can potentially support the maintenance of a comfortable and healthy indoor environment by controlling the air temperature, humidity and air quality. Many absorbent materials are being developed, tested and applied for absorbent-based heating, ventilating and air-conditioning systems. The design of these systems depends on the application and situation. Hence, the systems installed in actual buildings in different climates show their applicability and viability. Because buildings today require an increasing amount of energy for heating, ventilating and air-conditioning, the application of absorbent-based heating, ventilating and air-conditioning systems presents a potential alternative to costly traditional systems. These absorbent-based systems can lessen the building's energy consumption for the maintenance of its indoor environment. These systems also eliminate chemical contents in the air, such as VOCs, and biological microorganisms, such as bacteria and viruses. Hence, absorbent-based air handling systems are a potential alternative to typical air handling systems. These systems have several advantages: they are cheaper, smaller, require simpler maintenance and can operate on available energy sources. Therefore, further research and studies are needed to address the above issues and simultaneously educate the public (ordinary users) and developing countries on the benefits and advantages of using absorbent-based air-conditioning systems as alternatives to the widely used and established systems.

Contents

* Corresponding author at: *Enteria Grün Energietechnik, Davao 8000, Philippines*. Tel./fax: +63 82 305 2226.
E-mail address: enterian2@asme.org (N. Enteria).

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1. Introduction

The building sector is one of the primary energy consumers, accounting for almost 50% of the energy use in developed countries [1]. In the European Union, the residential and tertiary sectors are responsible for more than 40% of the final energy consumption [2]. In Japan, the energy consumption of the building sector is increasing every year, while the energy consumption of the transportation and industrial sectors is almost constant [3]. In Asia-Pacific Partnership on Clean Development and Climate (APP) countries, buildings are the top final energy consumer [4]. In developed countries, building energy conservation and implementation of energy efficiency have become part of several energy conservation programs [4,5]. These programs consist of utilizing alternative energy sources and developing energy efficient technologies. Because the global population and urbanization are continuously increasing, building energy consumption is expected to also continually increase [6]. Hence, the contribution of the building sector to the emission of greenhouse gases is also expected to increase [7]. Because most of the population spends almost 90% of their time indoors, the energy demand to maintain the indoor thermal environment and air quality constitutes a large percentage of a building's energy consumption. For example, in hot and humid tropical climates, the energy consumption of the building sector for air-conditioning and cooling system comprises a sizable share of the building's energy consumption [8,9]). For example, Fig. 1 shows the high energy consumption required for indoor air-conditioning systems in typical tropical office buildings. In addition, Fig. 2 shows the energy consumption for a typical tropical residential house, showing the large percentage of energy consumption for the air-conditioning system.

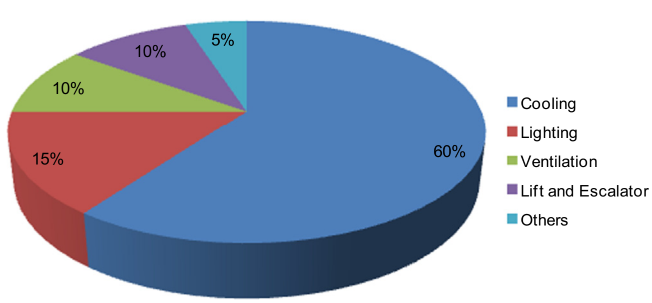


Fig. 1. Singapore breakdown of electric energy usage in typical office building [8].

Refrigerant-based systems are the most typical heating, ventilating and air-conditioning (HVAC) systems for buildings. Large buildings generally feature centralized heating, ventilating and air-conditioning systems that use chilled or hot water circulating in fan coil units to maintain the indoor temperature. In hot and humid climates, operating an air handling system to maintain the indoor thermal environment becomes energy intensive due to the high humidity content of the outdoor air [10]. The air-handling systems in buildings are energy intensive due to the cooling and re-heating of the processed air prior to its supply to the indoor environment. Fig. 3 shows the acceptable operative temperature and humidity in an indoor space based on ASHRAE 55-2004 [11]. In addition, maintaining a range of relative humidity is crucial for

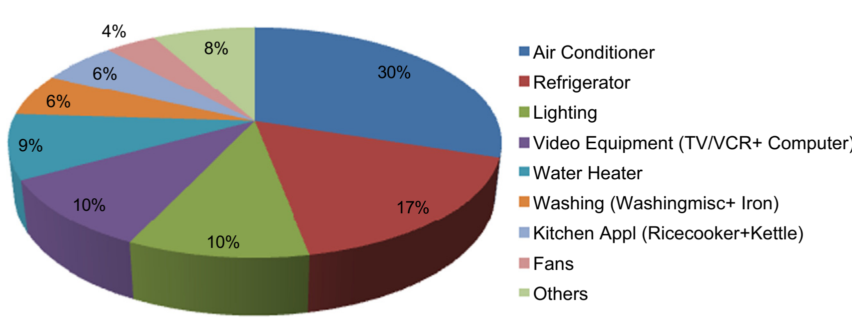


Fig. 2. Singapore breakdown of electric energy usage in residential building [9].

a healthy indoor environment. The relative humidity in indoor environments suggests that it can affect the incidence of respiratory infections and allergies [12]. Fig. 4 shows the importance of maintaining the relative humidity for a healthy indoor environment.

A variety of heating, ventilating and air-conditioning systems are more energy efficient than conventional systems [13,14]). Sorbent-based systems are one such alternative to conventional systems. The advantage of a sorbent-based system is its use of alternative energy sources. Open-cycle absorption air-conditioning systems are one of the alternatives to traditional systems, and it is particularly advantageous when attempting to remove moisture and microorganisms by passing the air over the absorbent surface to maintain the indoor thermal and air quality [15]. Open-cycle absorption air-conditioning systems utilize the capability of the absorbent to remove moisture in the air via the water vapor difference between the absorbent and the air. The moisture content and temperature of the air can be controlled by various designs. Several substances have been utilized as absorbents for open-cycle absorption air-conditioning systems. Open-cycle absorption air-conditioning systems have been installed to maintain the indoor building environments in various building types and climates.

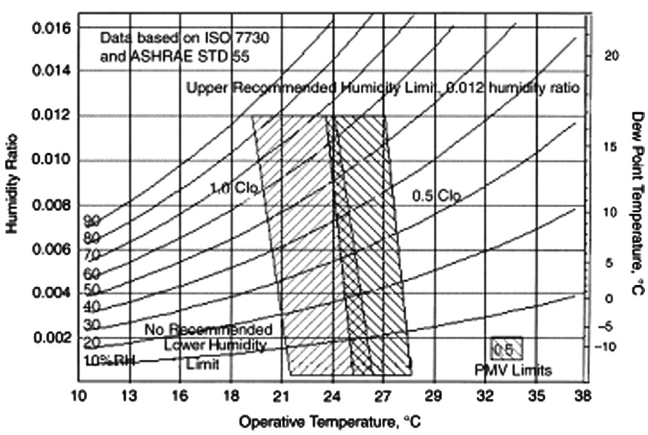


Fig. 3. Acceptable range of operative temperature and humidity for spaces that meet the criteria specified [11].

To fully understand the science and technology behind the research, development and application of open-cycle air-conditioning systems, this paper discusses the different open-cycle absorption air-conditioning technologies and their future development and applications. Because the handling of the absorbent and operation of the system both involve technical and economic challenges, this paper will provide significant insight to further investigate, develop and apply these systems to reduce the energy required to maintain a building's indoor environment. In addition, this paper discusses different absorbents used in the absorption processes, including their thermodynamic properties and advantages. This paper discusses the typical and new concepts and designs of dehumidifiers and regenerators, both with respect to the whole system and its coupling with conventional heating, ventilating and air-conditioning systems. Specifically, sample installations are discussed with regard to their applicability and potential, as well as the different possible applications of open-cycle absorption air-conditioning systems.

2. Absorbents

Absorbents are a vital component of the design and selection of dehumidifiers and regenerators. The selection of the absorbent for the dehumidifiers and regenerators depends on the investment cost, outdoor air conditions, indoor air conditions, and the source of thermal energy. Many classes and types of absorbents are available. Most absorbents are salt-based and have a high affinity towards water molecules, while some are based on aqueous substances.

2.1. Selection criteria

The selection of absorbents is based on the following important criteria: boiling point elevation, energy storage density, regeneration temperature, thermo-physical properties, availability, cost, corrosion effects, toxicity, density, and viscosity. These criteria are the most basic considerations when selecting absorbents for open-cycle absorption air-conditioning systems. The surface vapor pressure is the most important property among the properties of absorbents [16]. Park et al. [17] showed that adding four

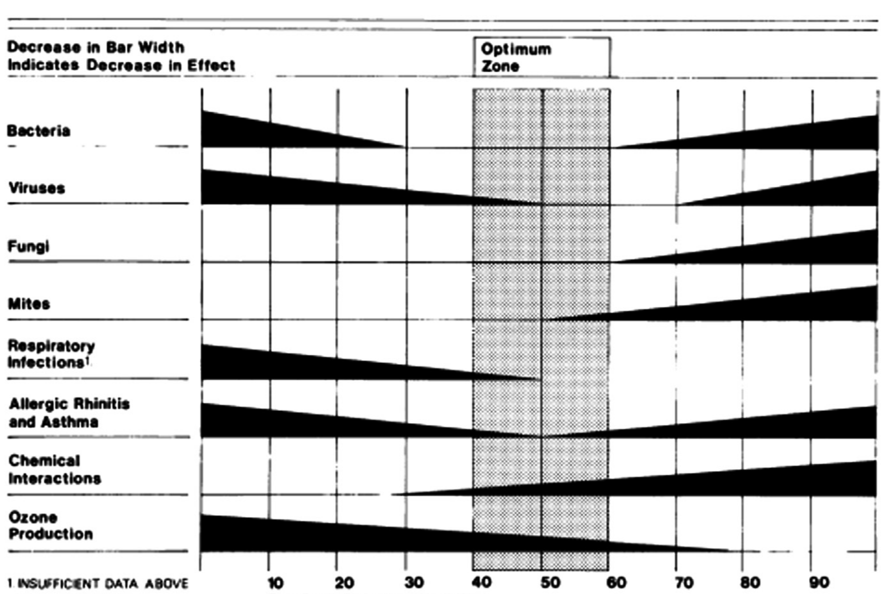


Fig. 4. Effect of relative humidity on bacteria, viruses, fungi, mites, respiratory infections, allergic rhinitis, asthma, chemical reactions, and ozone production [12].

Table 1
Comparison of the properties of six absorbents at 25 °C, to allow a fair comparison, a concentration giving an equilibrium relative humidity of ERH=50% has been chosen in each case, with the exception of sodium chloride where ERH=75%, this being the minimum achievable [19].

Property	Unit	Aqueous solution					
		$CaCl_2$	LiBr	LiCl	MgCl	ZnCl	NaCl
Cocentration (mass solute/mass solution)		0.36	0.39	0.26	0.31	0.52	0.26
Hygroscopicity (equilibrium RH)	%	50	50	50	50	50	75
Cost	US$/m³	560	7300	4600	450	1400	180
Abundance in seawater[a]	m³/m³	2.3×10^{-3}	4.0×10^{-6}	3.0×10^{-6}	1.3×10^{-2}	1.0×10^{-9}	9.0×10^{-2}
Density	kg/m³	1.35	1.38	1.4	1.29	1.58	1.2
Viscosity	mPa-s	4.6	1.8	2.5	6	4.7	1.8
Specific heat capacity	kJ/kg-°C	2.6	2.6	3	2.1	2.3	3.4
Thermal conductivity	W/m-°C	0.56	0.48	0.56	0.52	0.46	0.58
Diffusivity of water in the solution	10^{-9} m²/s	0.54	1.17	0.9	0.91	0.8	1.86
Differential heat of dilution	kJ/kg	80	no data	65	65[d]	no data	no data
Water absorption capacity[b]	kg/m³	85	84	91	76	120	n.a.
Human toxicity[c]	L	0.14	0.23	0.10	0.49	0.03	0.66
Ecotoxicity (Daphnia magna)	ml/L	4.9(2)	no data	0.06 (2)	4.3 (1)	0.001 (6)	20 (5)

[a] Volume of desiccant solution that could theoretically be extracted from unit volume of seawater, assuming 100% recovery speed.
[b] Mass of water that, on absorption in the solution, will cause a 10% relative increase in equilibrium relative humidity.
[c] Estimated lethal dose in humans scaled from LD50 values for rats.
[d] At 50 °C.

eight-carbon alcohol additives, such as noctanol, 2-octanol, and 3-octanol, lowers the vapor surface pressure of the absorbents. Adding water to calcium chloride (50 wt%) and calcium nitrate (20 wt%) significantly increased the vapor pressure drop compared with other absorbents [18]. Furthermore, the heat of absorption is an important parameter that describes the energy released during the absorption process. It also represents the minimum energy needed to reverse the reaction and release the absorbate from the absorbent. Other important factors in the selection of the absorbents are the moisture uptake capacity, heat of sorption, volatility and stability of the chemical composition. The chemical characteristics of the absorbents depend on their chemical composition. The moisture uptake of the absorbents is based on a chemical sorption process that releases heat (i.e., the heat of sorption).

2.2. Common materials

The most common absorbents are lithium bromide, lithium chloride, calcium chloride and triethylene glycol. Other possible candidates for absorbent materials include salt-based solutions or related materials that attract water molecules. Examples of alternative absorbents include potassium chloride and sodium chloride. Other candidates consist of a mixture of the commonly used absorbents mentioned above. Table 1 shows a summary of common absorbents and their thermo-chemical properties, environmental impact, human toxicity and cost for comparison purposes.

2.2.1. Aqueous solutions of salts

2.2.1.1. Lithium chloride. The lithium chloride has low vapor pressure at given temperature but it is expensive [16]. Fig. 5 shows a psychrometric chart of LiCl. According to Ameel et al. [21], absorbers that utilize a lithium chloride solution at 35°C require approximately five times the area of an absorber utilizing lithium bromide to achieve the same sorption performance. Furthermore, lithium chloride solutions are not practical as absorbent at a temperature of 45°C or higher due to solubility limitations [21]. However, the dehumidification performance of lithium chloride is better for a given absorbent mass flow rate. At the same absorbent volumetric flow rate, the dehumidification performance of lithium chloride is almost the same as that of lithium bromide. Al-Farayedhi et al. [22] used structured packings to dehumidify and regenerate three absorbents (calcium chloride, lithium chloride, and a mixture of 50% calcium chloride and 50% lithium chloride). They showed that lithium chloride has the highest liquid-phase mass transfer coefficient of the three absorbents due to its molecular weight. Compared to a pure LiCl solution, the dehumidification performance of a mixed LiCl and $CaCl_2$ solution improved by 20% [23].

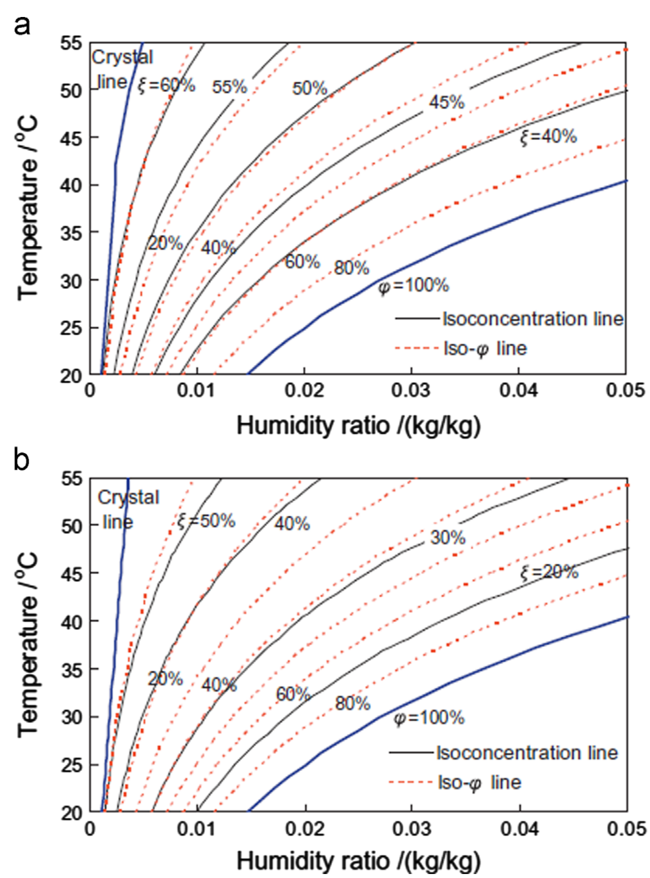


Fig. 5. Status of the commonly used absorbents in the psychrometric chart: (a) Lithium bromide (LiBr); (b) Lithium chloride (LiCl) [20].

2.2.1.2. Lithium bromide. The cost and vapor pressure of lithium bromide (LiBr) lies between those of calcium chloride and lithium chloride [16]. The regeneration performance of lithium bromide is almost the same as that of lithium chloride. The regeneration performance of lithium bromide is better than that of lithium chloride. Lithium chloride and lithium bromide are the most common absorbents used in open-cycle absorption air-conditioning systems. Furthermore, the two materials have the same coefficient of performance [20]. Fig. 5 shows a psychometric chart of LiBr.

2.2.1.3. Calcium chloride. Calcium chloride (CaCl) is the cheapest of the discussed materials, but its relative vapor pressure is high at the same given temperature [16]. Lithium chloride and calcium chloride have a low viscosity and are highly soluble over a considerable temperature range. These properties ensure that the absorbent does not solidify, which is a requirement for its effectiveness [24]. At the same absorbent volumetric flow rate, the dehumidification performance of lithium chloride solution is slightly better or similar to that of lithium bromide, but the regeneration performance of lithium bromide is better than that of lithium chloride. The COPs (coefficient of performance) of open-cycle absorbent air-conditioning systems that use these two absorbents are similar [20]. Using varying weight combinations of calcium chloride and calcium nitrate, i.e., a mixture of 50 wt% calcium chloride and 20% calcium nitrate in water, significantly decreased the vapor pressure [18].

2.2.2. Aqueous solutions of organic compounds

Triethylene glycol has high viscosity with a very low surface vapor pressure, which results in its evaporation to flowing air [16]. Chen et al. [25] studied a mixed-solvent open-cycle absorption air-conditioning system containing {(40.0 wt%) glycol+salt+water} using diethylene, triethylene, and tetraethylene glycol and magnesium chloride as the salt. Their study indicated that the density of the above-mentioned absorbents decreased with the temperature increased and increased with increases in the salt concentration. In the study, the vapor pressure increased as the temperature increased and decreased as the salt concentration increased. These findings indicate that their studied absorbents are a promising alternative to conventionally used absorbents. One of the advantages of glycol-based absorbents is their lower regeneration temperature. However, glycol-based absorbents are corrosive and toxic, which limits their applications. Glycol-based substances include diethylene glycol (DEG), triethylene glycol (TEG), tetraethylene glycol (T4EG), propylene glycol (PG), and dipropylene glycol (DPG). Chung and Luo [25] experimentally studied the vapor pressures of the aqueous desiccants lithium chloride, lithium bromide, calcium chloride, ethylene glycol, propylene glycol, and their mixtures at their typical operating concentrations and at temperatures from 298 K to 313 K. The results show that the vapor pressure of an absorbent solution is an important parameter for predicting the effectiveness of the system that also provides important data on the vapor pressure for the potential absorbent solutions [25].

2.2.3. Other aqueous solutions

Certain important requirements cannot be addressed by ordinary absorbents, such as a low vapor pressure, high boiling point, high latent heat of condensation and dilution, low crystallization point, easy handling at low temperature, low viscosity, high density, and low cost [26]. Hence, alternative potential absorbents have been investigated, such as calcium chloride and lithium chloride mixtures, water+lithium bromide+potassium acetate, water+lithium bromide+sodium lactate, lithium bromide aqueous solution and lithium bromide–water absorbents. Mixtures of calcium chloride and lithium chloride show a considerable increase in the mass transfer coefficient compared with calcium chloride absorbents [22]. Fig. 6 shows the activity map of lithium chloride (LiCl) and calcium chloride ($CaCl_2$). Patil [27], Ahmed et al. [28], Uemura [29] and other researchers have determined the thermodynamic properties of single absorbents. Conde (2004) [30] developed calculation models for the thermo-physical properties of aqueous absorbents of lithium chloride and calcium suitable chloride for use as absorbents in open-cycle absorption air-conditioning systems. de Lucas et al. [31] provided the thermodynamic properties of water+lithium bromide+potassium acetate and water+lithium bromide+sodium lactate. Ahmed et al. [28] used simple mixing rules to predict the thermodynamic properties of absorbents. McNeely [32] provided the thermodynamic properties of aqueous lithium bromide absorbents. Kaita [33] developed a thermodynamic equation for lithium bromide–water absorbents. Mixed lithium chloride and calcium chloride absorbents could improve the dehumidification effect by more than 20% compared to the pure lithium chloride absorbent [23]. Other potential absorbents include lithium chloride, zinc chloride [21], and magnesium chloride [34]. Magnesium chloride is safer both to humans and the environment [34]. Ertas et al. [24] showed that the vapor pressure of a lithium chloride and calcium chloride absorbent is lower than that of pure calcium chloride, which increased the performance of calcium chloride. Sulfonic-type cation-exchange resins are excellent absorbents for drying organic liquids. The use of Dowex 50W resin for drying has been extensively investigated using ethanol and 1, 1, 1-trichloroethane as examples of relatively polar and nonpolar materials, respectively. Of the resin variables studied, the ionic form is the most important. Luo et al. [35] investigated the ionic liquid 1-ethyl-3-methylimidazolium tetrafluoroborate ([EMIM]BF4). The study showed that this absorbent has lower corrosion to metal and will not crystallize at high mass concentration. It will dry nonpolar organic liquids to less than 1 p.p.m. (part per million) of water and exhibits high capacities. It can be regenerated at the relatively low temperature of 240°F to 280°F. One important advantage of cation-exchange resins is their relatively low regeneration temperature of 240°F to 280°F compared with the 400°F to 600°F temperature range recommended for synthetic zeolite materials [36].

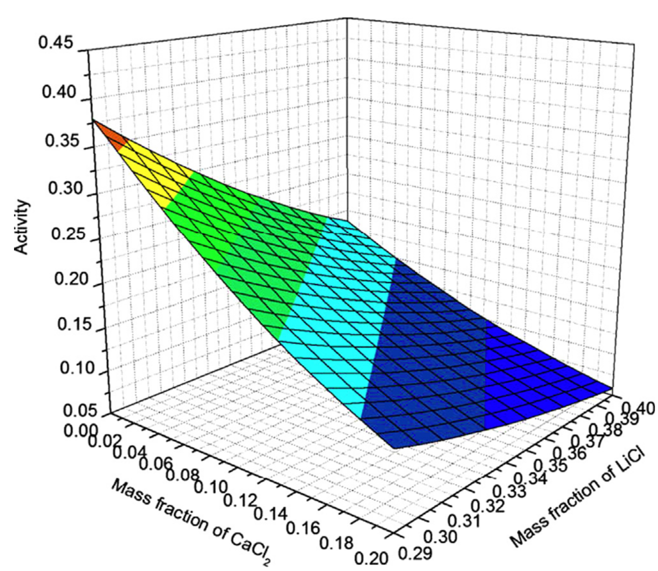


Fig. 6. Activity map of Lithium chloride (LiCl) and Calcium chloride ($CaCl_2$) solution at 25°C [23].

The mixed-solvent absorbents (aqueous-organic compound solutions containing salt (glycol/salt/water)) mentioned by Chen et al. [37] include DEG/LiCl/H_2O (diethylene glycol lithium chloride water), TEG/LiCl/H_2O (triethylene glycol lithium chloride water), T_4EG/LiCl/H_2O (tetraethylene glycol lithium chloride water), PG/LiCl/H_2O (propylene glycol lithium chloride water), DPG/LiCl/H_2O (dipropylene glycol lithium chloride water), DEG/LiBr/H_2O (diethylene glycol lithium bromide water), TEG/LiBr/H_2O (triethylene glycol lithium bromide water), T_4EG/LiBr/H_2O (tetraethylene glycol lithium bromide water), PG/LiBr/H_2O (propylene glycol lithium bromide water), and DPG/LiBr/H_2O (dipropylene glycol lithium bromide water). Li et al. [26] investigated the addition of the ionic liquids (ILs) 1,3-dimethylimidazolium chloride ([Dmim]Cl) and 1,3-dimethylimidazolium tetrafluoroborate ([Dmim]BF_4). The data showed that the addition of these liquids to aqueous solutions of lithium bromide (H_2O+LiBr) and lithium chloride (H2O+LiCl) lowered the vapor pressure. Tsai et al. [38] studied the vapor pressures, densities, and viscosities of mixed solvent absorbents over a temperature range from 303.15 K to 343.15 K. Four ternary mixtures, (TEG+H_2O+LiCl), (PG+H_2O+LiCl), (TEG+H_2O+LiBr), and (PG+H_2O+LiBr), were selected. Each ternary system included four mixtures that varied from 4 to 25% salt mixed with various glycols (50-80 mass%). The vapor pressures of the aqueous-organic systems with salt were lower than those of conventionally used liquid absorbents. This finding indicates that aqueous-organic systems that include salt could potentially serve as absorbents.

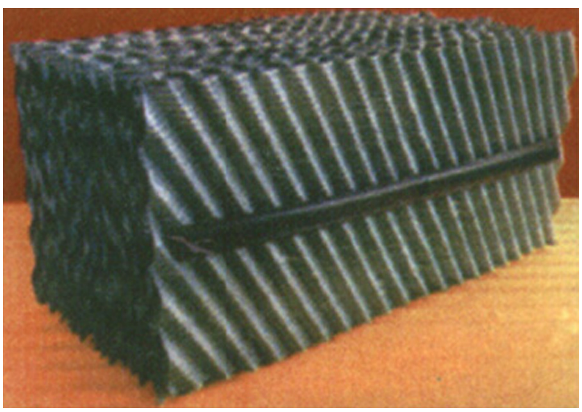


Fig. 7. Sample of structured packing [16].

3. Absorbent heat exchanger design

The dehumidifier and the regenerators are the most important components of the open-cycle absorption air-conditioning system. The performance of the entire system relies on the performances of these components to remove moisture from the air and reactivate the absorbent for reuse. Hence, the structural design of these components is important. Packed-bed columns are often employed in open-cycle absorption air-conditioning systems. Spray-type systems are also used. However, the selection of these designs depends on the available area.

3.1. Structured packing

Among the structured packing materials, sheet-type packings have a lower irrigated pressure drop than gauze-type structured packings. Structured packings have a lower pressure drop and higher capacity compared with random packings [39]. Structured packings include cellulose rigid media pads, wood grids, expanded

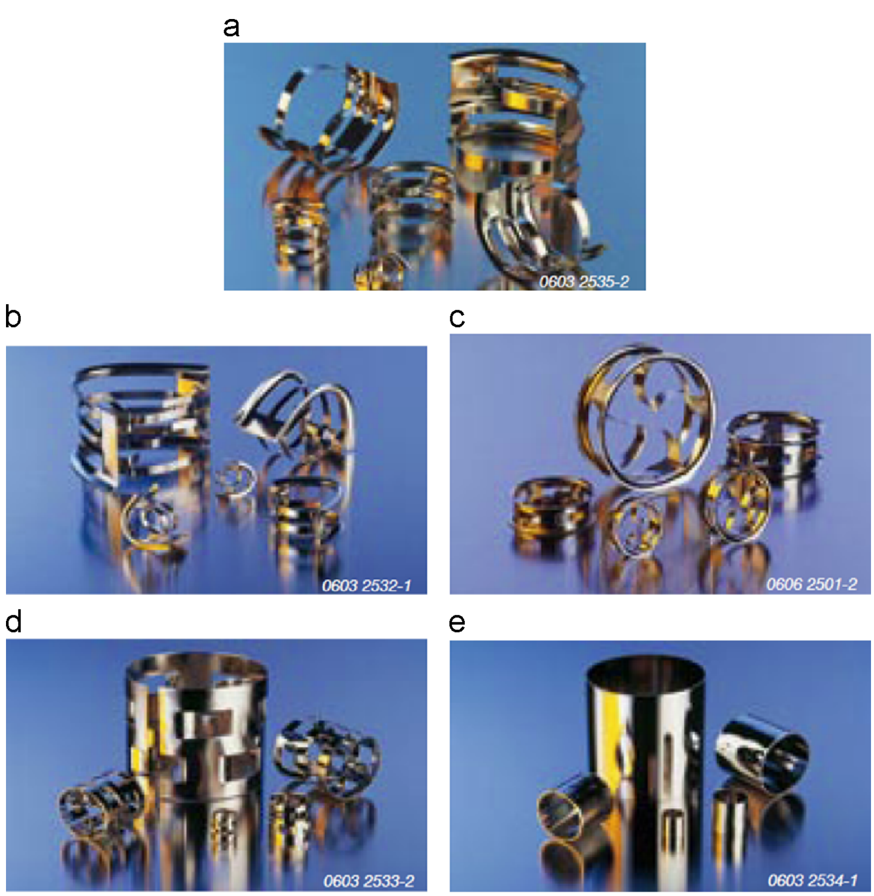


Fig. 8. Sample of unstructured packing materials [50]. (a) Nutter Ring, (b) I Ring, (c) C Ring, (d) D Ring and (e) R Ring.

metal lash packing, and double spiral rings. Fig. 7 shows an example of a structured packing. Al-Farayedhi et al. [22] demonstrated that a mixture of calcium chloride and lithium chloride solution considerably increased the mass transfer coefficient compared with a pure calcium chloride solution in a gauze-type structured packing tower. The performance of two different structured packings, wood and aluminum, in a packed bed column (dehumidifier) using triethylene glycol (TEG) as the absorbent under hot and humid conditions was investigated. The moisture removal rate was found to positively correlate with the inlet TEG concentration, TEG flow rate and airflow rate. This effect was observed for both the wood and the aluminum packings. In addition, the moisture removal rate was increased by increasing the inlet air temperature for the aluminum packing only. The effectiveness of the column was increased by increasing the TEG flow rate and inlet TEG temperature for the two packings [40]. An experimental study to investigate the performance of an absorbent air dehumidifier equipped with a structured packing made of wood has been conducted for three different densities using triethylene glycol (TEG) as the absorbent [41]. The structured packing densities were 77, 100 and 200 m^2/m^3. A packing density of 200 m^2/m^3 lowered the effectiveness of the column compared to the other two packing densities when the airflow rate, inlet concentration and absorbent flow rate were increased. However, the effectiveness increased when either the inlet temperature of the air or absorbent was increased. Heat and mass transfer processes have also been studied in a cross flow absorbent dehumidifier, in which wet durable honeycomb paper constituted the packing material [42]. The coefficients of heat transfer in the absorbent dehumidification differed between the absorbent side and the gas side because the mixing heat generated in the dehumidification heats not only the process air but also the absorbent. Gandhidasan [43] studied the regeneration of weak absorbents in a packed bed using a simple model in which the absorbent was heated by two different methods. In method A, the absorbent was heated in a heat exchanger by a hot fluid (water). The study indicated that a higher heating fluid inlet temperature and higher heat exchanger effectiveness increased the rate of evaporation. In method B, the absorbent was heated by a conventional energy source. Using this method, the evaporation rate increased with the heat input, and the regeneration rate decreased as the scavenging airflow rate increased. The expressions derived from this study for both methods of heating are valuable for a quick estimation of the water evaporation rate. Fumo and Goswami [44] showed that the following design variables have the greatest impact on the performance of the dehumidifier: the absorbent concentration, absorbent temperature, airflow rate, and air humidity ratio. The following design variables have the greatest impact on the performance of the regenerator: the absorbent temperature, absorbent concentration, and airflow rate. Goel and Goswami [45] proposed a new design of a falling film absorber that could considerably reduce the absorber size without penalizing the vapor and coolant side pressure drops. They presented a new concept for forming a falling film between the horizontal coolant tubes by a flow guidance medium, such as a mesh. This approach reduces the system's size by approximately 25% for a given set of operating conditions. The proposed design induced thorough mixing of the absorbent film while it alternatively flowed over the mesh and coolant tubes. In addition, the simplicity of the design facilitates its incorporation in existing falling film absorbers [45]. Hence, this concept is suitable for upgrading installed systems to increase their performance.

3.2. Random packing

Different types of traditional random packings, such as Raschig rings, Intalox saddles, and Berl saddles, are widely used in industry, and they are available in the market in a variety of materials. Among random packing materials, ceramic and plastic packings are generally preferred for a system operating with absorbents because the packings are inert to the absorbents. Plastic random packings are suitable for the dehumidification of air with absorbents. These packings are lightweight, easy to install, have a lower pressure drop, low cost, and do not suffer from corrosion. However, they cannot be used for the regeneration process because of the high temperature involved in the process. Gandhidasan [46] used ceramic random packings to study the influence of the effective interfacial area in absorbent material contactors. Their results indicate that the air mass flux and air density do not influence the effective interfacial area. Thus, their effects can be neglected for absorbent contactors. Furthermore, the effective interfacial area estimated for an absorbent-air contact system is approximately 17% lower than that of a water-air system. Larger random packings have been found to provide a smaller interfacial area. The interfacial area of Ceramic Berl saddles is larger than that of ceramic Raschig rings [46]. Among the random packing materials, Raschig rings give the highest irrigated pressure drop. Although random packings provide good contact between the air and the absorbent, the required absorbent flow rates for good wetting and the air pressure drops are generally high [47,48]. In addition to being influenced by the flow pattern, heat and mass transfer coefficients, and flow rates of the air and fluid, the heat and mass transfer characteristics are somewhat affected by the conditions of the inlet air and inlet fluid [49]. Fig. 8 shows a variety of random packing materials. Longo and Gasparella [51] conducted experimental tests and a theoretical analysis of the chemical dehumidification of air using an absorbent and absorbent regeneration in an absorption/desorption column with random packings. The experimental tests included dehumidification and absorbent regeneration runs carried out with the traditional hygroscopic salt solutions H_2O/LiCl and H_2O/LiBr and the new salt solution H_2O/KCOOH over typical operating ranges of air-conditioning applications. The dehumidification performances of the traditional solutions H_2O/LiCl and H_2O/LiBr were better than that of the new solution H_2O/KCOOH. However, the latter performed better in regeneration tests, was less corrosive and expensive than traditional desiccants, and was fully compatible with the environment. These features make it suitable to reduce the humidity in technical applications of interest [51].

3.3. Spray towers

The performances of dehumidifiers and regenerators can be increased using alternative designs. Spray-type systems are a good option to increase the surface area for heat and mass transfer. Warnakulasuriya and Worek [52] indicated that atomization increases the heat and mass transfer rates because the exposed area of the brine solution was increased compared to the falling film technique used in a conventional absorber. This finding shows that the drop size, which controls the surface area available to absorb water vapor, is a very important parameter. When the drop speed increases, the resident time of the drops decreases, which decreases the absorption rate. However, as the drop speed increases, the Reynolds number increases, which increases the drop circulation. Counteracting effects must also be considered to ensure that the overall net effect is positive.

3.4. Membrane exchangers

Membranes are suitable to eliminate the direct contact between the absorbent and the air while avoiding the mass carry-over of the absorbent to the air [53]. Fig. 9 shows a membrane air dehumidifier. Jain et al. [56] investigated membrane

dehumidifiers in tropical climates. Their findings indicate that absorbent carry-over was avoided. Huang et al. presented a detailed heat and mass transfer analysis of this type of heat exchanger to evaluate the flow and membrane configuration [57]. The DEVap, which stands for "*desiccant-enhanced evaporative*" air conditioner, is a novel concept that uses membrane technology to combine the efficiency of evaporative cooling and the drying potential of salt-based absorbents [58]. Fig. 10 shows a diagram of a DVAP conditioner. Membranes with lower thermal conductivities and higher porosities improve the performance of single-membrane designs, while thinner membranes improve the performance of air-gap designs [53]. Fig. 11 shows a non-contact absorbent dehumidification concept based on hollow fibers [60]. The main advantage of this system is the avoidance of absorbent carry-over because the absorbent flows inside the fiber tube while the air is outside the fiber tube, such as in a shell-and-tube heat exchanger. Jain et al. [56] studied the performance of absorbent dehumidification systems using calcium chloride and lithium chloride. An indirect contact air-absorbent dehumidifier was used to avoid the carryover of the absorbent into the air stream. Calcium chloride resulted in a small change in the specific humidity in the range of 0.6–1.77 g/kg. The effectiveness of the dehumidifier was found to range between 0.25 and 0.44, while that of the regenerator was between 0.07 and 0.80. Lithium chloride more effectively dehumidified the air; the change in specific humidity ranged between 3.67 and 5.86 g/kg, and the effectiveness ranged between 0.36 and 0.45.

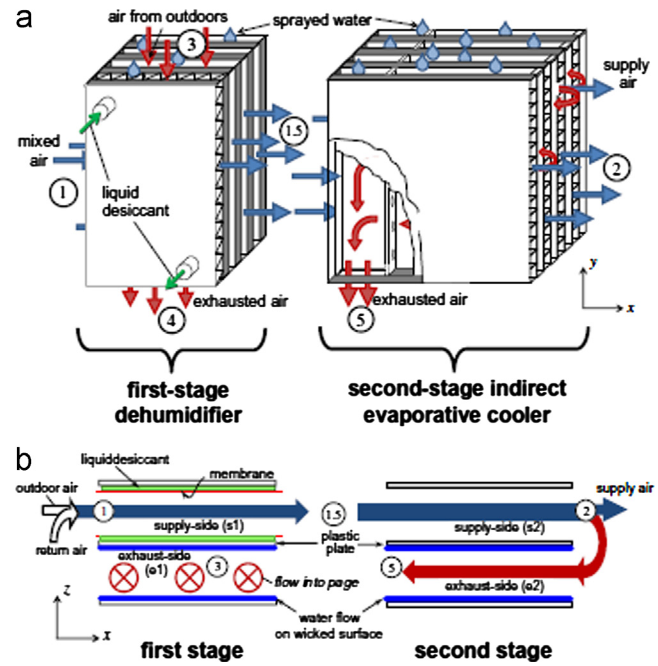


Fig. 10. Diagram of the DEVAP air conditioner: (a) stacked channel pairs and (b) top view of the channel pair [59].

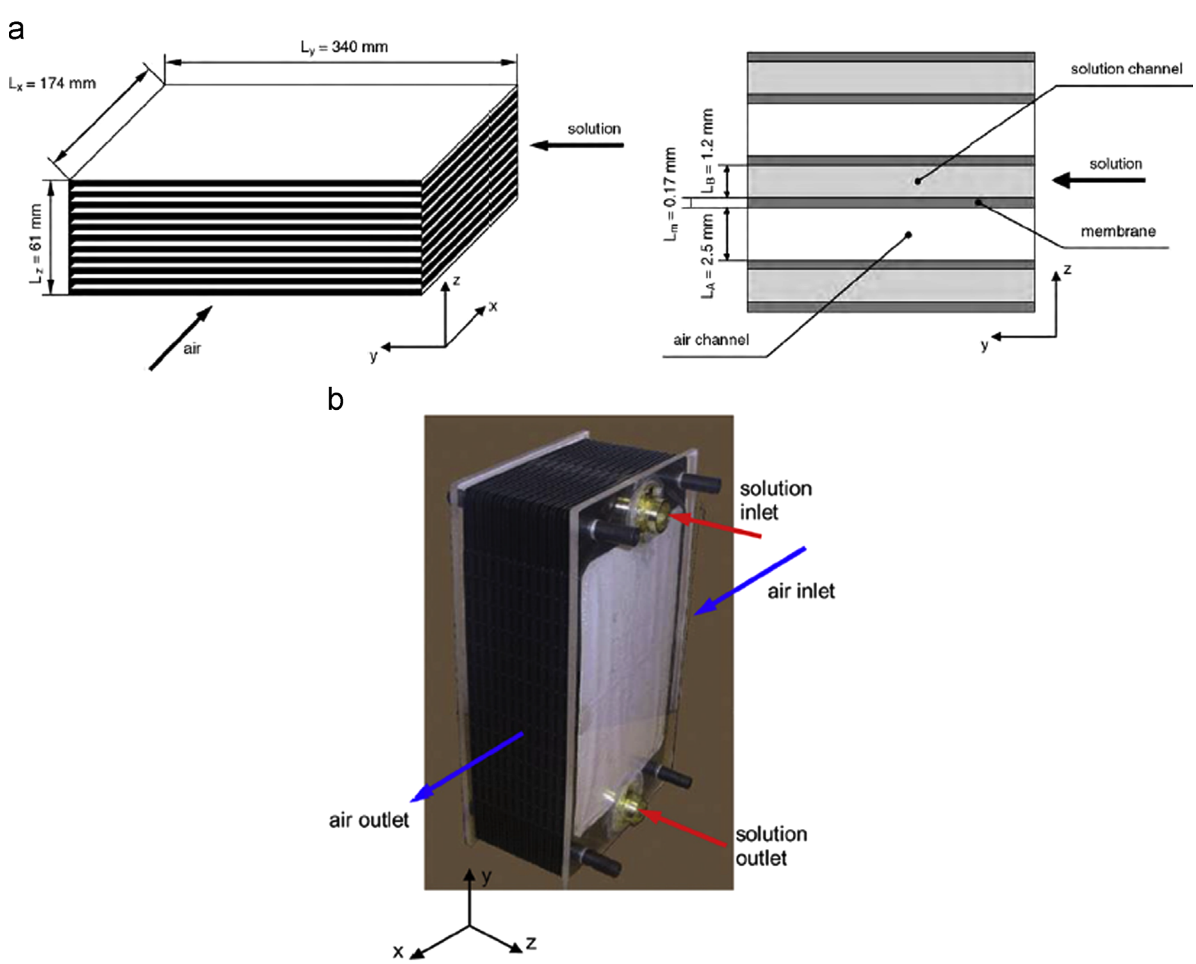


Fig. 9. Membrane air-dehumidifier: (a) Diagram of membrane air-dehumidifier with arrangement of air, membrane and absorbent channels [54] and (b) Actual view of the membrane air-dehumidifier [55].

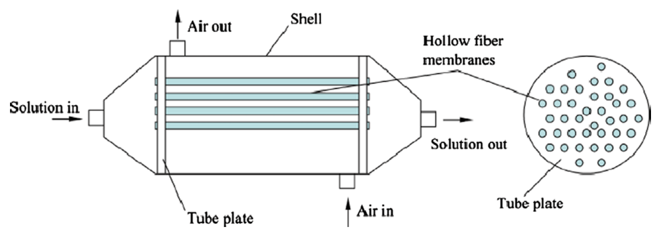


Fig. 11. Schematic diagram of hollow fibre membrane module for air-dehumidification [60].

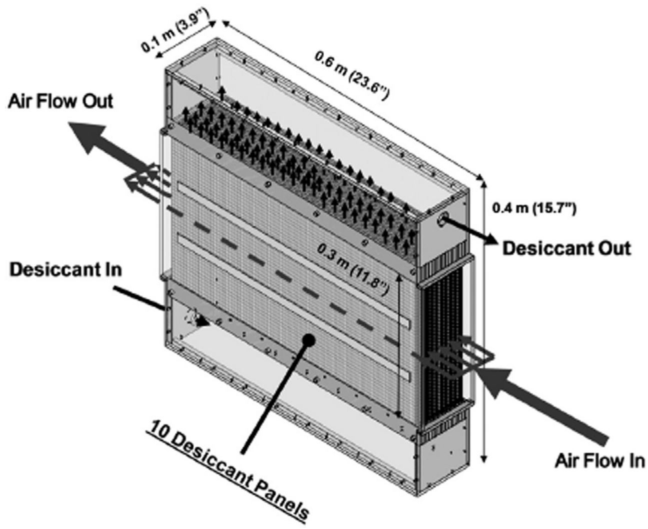


Fig. 12. The liquid-to-air membrane energy exchanger (LAMEE) prototype [61].

An experimental run-around membrane energy exchanger (RAMEE) was designed, constructed and tested (See Fig. 12). The RAMEE system consisted of two cross flow absorbent-to-air membrane energy exchangers (LAMEEs) coupled with an absorbent loop [61]. Based on the studies, there are features to be optimized to increase the performance. First, counter-flow designs, where the absorbent flows in the opposite direction as the air, should perform better. Second, the heat and moisture transfer properties are membrane-specific, which affects the system performance.

3.5. Others

Solar collector/regenerator (C/R) (Fig. 13) are systems that use absorbent combine solar photothermal transformation and the regeneration of the absorbent to effectively regenerate the absorbent in a solar energy-driven absorbent air-conditioning system [62]. This type of system can regenerate the absorbent at lower temperatures [63]. The effective solution proportion (ESP) also affects the regeneration performance. When the ESP falls from 100% to 62%, the regeneration efficiency increases to 45.7%, the storage capacity increases to 44%, and the solution concentration between the outlet and inlet of the regenerator increases by 70%. These findings indicate that a lower ESP favors the absorbent regeneration [64]. The inlet conditions of the air stream and solution film also affect the regeneration performance; increasing the inlet temperature of the air and solution increased the concentration by 2.9–3.5%/°C and 5.3%/°C, respectively. Decreasing the inlet humidity ratio of the air stream and inlet concentration of the solution increased the absorbent concentration by approximately 6.2%/(g/kg) and 0.9%/(g/kg), respectively. Compared to the parallel flow regeneration, the outlet solution concentration for the counter flow regeneration system increased by approximately 10% under various working conditions [65]. Innovative packings, such as wire

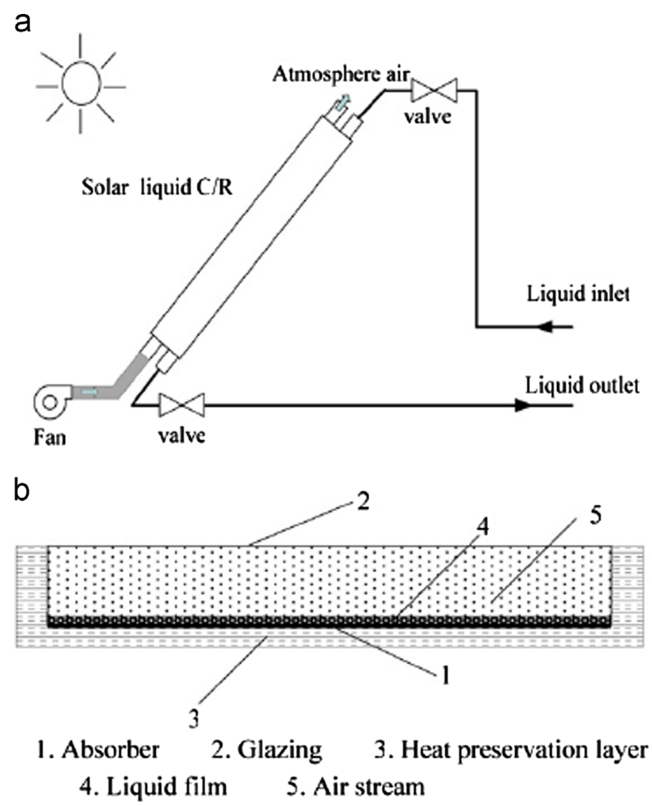


Fig. 13. Schematic diagram of the combined solar-absorbent collector-regenerator: (a) Schematic diagram; (b) cross sectional view [62].

mesh packing, have also been used to eliminate carry-over [66]. Another proposed method to eliminate carry-over is the direct injection of air into the solution of absorbent instead of passing the air along the surface of the flowing absorbent [67]. This method showed an effectiveness of 0.87 during dehumidification and 0.92 during humidification. The mass transfer coefficient reached 28 kg/s-m^2. The membrane-based desiccant regenerator concept is based on the reverse osmosis (RO) used in the desalination of seawater based on the studies of Al-Farayedhi et al. [68]. These studies show that the pressure required to regenerate calcium chloride is less than that of lithium chloride for the same operating conditions. The energy required for a mechanical regeneration system can be reduced with a higher recovery percentage [69].

4. Heat exchanger arrangement

The flow arrangement between the air and the absorbent is an important factor for the sizing and design of both the dehumidifier and regenerator. In general, dehumidifiers feature three simple flow patterns: parallel flow, counter flow and cross flow for high flow systems [16]. The design of the regenerator is similar to that of the dehumidifier. The only difference is the direction of heat and mass transfer between the surfaces of absorbent and the air.

4.1. Cross-flow

The cross flow dehumidifier is popular in engineering applications due to the small area required for its installation. However, it has lower heat and mass transfer effectiveness than counter flow dehumidifiers. Liu et al. [67] used Celdek structured packings to show that the moisture removal rate positively correlated with the air and absorbent flow rate, air inlet humidity ratio and absorbent concentration, and it negatively correlated with the absorbent

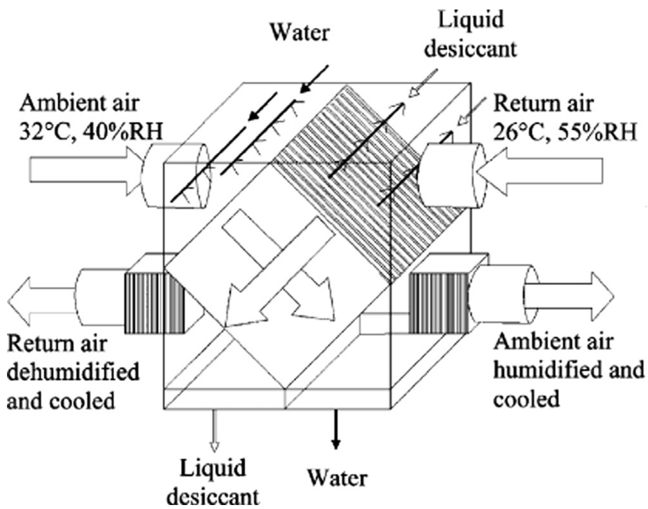


Fig. 14. Schematic diagram of the cross-flow heat exchanger absorber unit (HEAU) [72].

inlet temperature. Furthermore, the study showed that the dehumidifier effectiveness positively correlated with the absorbent flow rate and inlet temperature and negatively correlated with the airflow rate. The packing material in cross flow absorbent dehumidifiers consists of a wet durable honeycomb paper. Dai and Zhang (2004) [70] showed that the coefficients of heat transfer in the absorbent dehumidification differ between the absorbent side and gas side because the mixing heat generated in the dehumidification heats not only the process air but also the absorbent. Saman and Alizaldeh [70] investigated a cross-flow plate heat exchanger as a dehumidifier and cooler. Three sets of experiments were conducted to study the indirect evaporative cooling of the primary stream by the secondary air stream, where only an absorbent was used without indirect cooling and the primary air stream was indirectly evaporatively cooled by the secondary air stream and dehumidified by the absorbent sprayed into the primary side of the exchanger. The findings indicate that the effectiveness and dehumidification of this heat exchanger was maximized at a specific airflow rate. Furthermore, the findings indicate that the dehumidification efficiency increases as the primary air inlet temperature and humidity ratio increase. Gao et al. [71] showed that increasing the height, width and thickness of the dehumidifier increased the performance without increasing the pressure loss. Fig. 14 shows a schematic diagram of a cross-flow air dehumidifier.

4.2. Counter-flow

The counter-flow arrangement is not as popular in application as the cross-flow arrangement. However, it is the most widely used flow pattern for dehumidifier design purposes. Fig. 15 shows a schematic diagram of a counter-flow dehumidifier/regenerator. Ali and Vafai investigated inclined parallel counter-flow arrangements for falling film absorbents and air [74]. They also investigated the effect of the incline on the enhancement of the dehumidification, air-cooling and regeneration processes. The results show that the incline significantly affected the dehumidification process, air-cooling and regeneration for both parallel and counter-flow. Furthermore, the dehumidification and cooling processes required low air Reynolds numbers, while the regeneration process required a high air Reynolds number. A low absorbent flow enhanced the regeneration process, and a high absorbent flow augmented the dehumidification and cooling processes for an inclined parallel flow channel. High inlet air temperatures and low absorbent inlet concentrations resulted in improved dehumidification. Increasing the volume fraction and thermal dispersion increased the effective thermal conductivity of the absorbent. However, the enhancements in the dehumidification, cooling, and regeneration processes were minimal due to the small thickness of the absorbent film. Radhwan et al. studied the effects of varying the airflow rate, absorbent flow rate and bed geometry in addition to the effect of varying the air and absorbent inlet conditions [73]. The air flowed in the opposite direction of the absorbent ($CaCl_2$). The inlet temperature of the absorbent during the air dehumidification process significantly affected the other parameters, while the air inlet temperature had a negligible effect. Higher air and absorbent temperatures also enhanced the absorbent regeneration process, but at different ratios. The study showed that both the air and absorbent flow rates had negligible effects on the bed exit humidity ratio of air, whereas the absorbent flow rate significantly affected the bed exit moisture content of the absorbent. Increasing the airflow rate also enhanced the absorbent regeneration (air humidification) process. The product *(LAs) "over-all heat transfer coefficient and surface area"* increased and the exit air humidity decreased irrespective of the inlet moisture content of the absorbent. Gao et al. [71] conducted a numerical heat and mass transfer analysis of a cross-flow absorbent heat exchanger. The results show that the thickness, width and height affected the performance of the dehumidifier. These parameters could be varied to increase the performance without significantly increasing the pressure loss. Koronaki et al. [75] presented a study of the performance of a counter-flow absorbent dehumidifier. The three most commonly used absorbents, namely LiCl, LiBr and $CaCl_2$, were compared. The analysis showed that open-cycle absorption air-conditioning systems using LiCl performed better than those using LiBr and $CaCl_2$ under the same operating conditions. Even though the dehumidification efficiencies of the three absorbents were similar at high humidity ratios, the performance of LiCl was much more stable and predictable than that of $CaCl_2$. Saman and Alizadeh [76] predicted the performance of a system using a parallel configuration, as opposed to a counter-flow arrangement. Their findings indicate that this flow arrangement did not significantly affect the thermal performance of the absorber. Based on this finding, parallel configurations may be more desirable because they yield smaller pressure drops in the primary and secondary air compared to counter-flow arrangements. Liu et al. [49] showed that air and absorbents in a counter-flow configuration yielded a better dehumidification performance, while parallel-flow configurations showed the poorest performance at the same conditions. This improvement could be attributed to a more uniform mass transfer driving force in the counter-flow configuration.

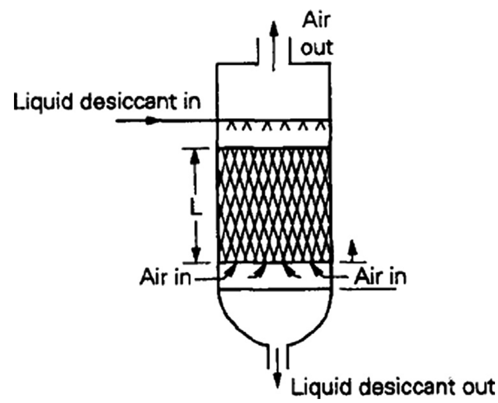


Fig. 15. Schematic diagram of the counter-flow absorbent dehumidifier/regenerator [73].

4.3. Cooled/heated exchangers

As opposed to adiabatic absorbent dehumidifiers, cooled absorbent dehumidifiers are based on the combined cooling of the

absorbent while absorption process is taking place, as shown in Fig. 16. This type of process increases the sorption due to the reduced increase of the water vapor pressure at the surface of the absorbent. Adiabatic dehumidifiers can be found over a wide range of industrial and residential applications; they offer a large air-absorbent contacting area with a relatively simple geometric configuration. In addition, their mass and heat transfer efficiency is high. However, these systems can potentially impose a large pressure drop on the process air when it flows through the packing materials. Moreover, the increase in the temperature of the absorbent during the moisture removal process adversely impacts the performance of the dehumidifier, which in turn decreases the accuracy of the humidity and temperature control of the process [16]. Bansal et al. [78] experimentally compared adiabatic and cooled absorbent dehumidifiers. The effectiveness was maximized between 0.55 and 0.706 with simultaneous cooling, and between 0.38 and 0.55 without cooling. The maximum amount of moisture removed was 0.005 kg/kg of dry air with cooling and 0.0034 kg/kg of dry air without cooling [78]. Khan [79] presented a heat and mass transfer performance analysis of internally cooled absorbents. This study found that the performance is a strong function of the water-to-air mass flow rate ratio (WAMR), carried-over regenerator heat, coolant water inlet temperature, number of transfer units (NTU), and the absorbent operating concentration. Furthermore, the sensible load-removal performance is more sensitive to variations in these parameters than the latent load-removal performance for an absorber of this nature. The carried-over regenerator heat adversely affects the performance; however, the use of a heat exchanger along with a higher coolant mass flow rate in the top portion of the absorber can help improve the performance. Saman and Alizaldeh [76] presented a cross-flow type heat exchanger for use as an absorbent absorber (dehumidifier) and indirect evaporative cooler. The results demonstrate that the proposed absorber will not offset both the latent and sensible load of the primary air. Therefore, an auxiliary cooler or more dehumidification/indirect evaporative cooling stages will generally be required to meet the sensible and latent load in a typical comfort application. The behavior of the internally cooled dehumidification process was compared with that of the adiabatic dehumidification process [80]. The results suggested that the cooling efficiency decreased as the cooling water temperature increased, and cooler absorbents increased the mass transfer coefficient. Furthermore, Yin et al. [81] reported that the internally cooled dehumidifier shown in Fig. 17 could also provide a better dehumidification performance compared with the adiabatic process; however, its performance was not as good as that of the internally heated regenerator. To reduce the moisture transfer resistance (MTR) and improve the dehumidification performance of internally cooled dehumidification systems, the pre-cooling should be centralized ahead of the absorbent inlet when

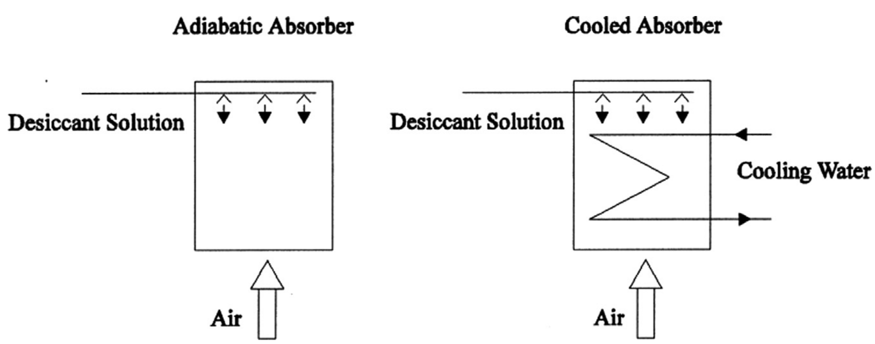


Fig. 16. Schematic difference between the adiabatic and cooled dehumidifier for the dehumidification of air. This diagram can be used also for heated regenerator instead of heater air [77].

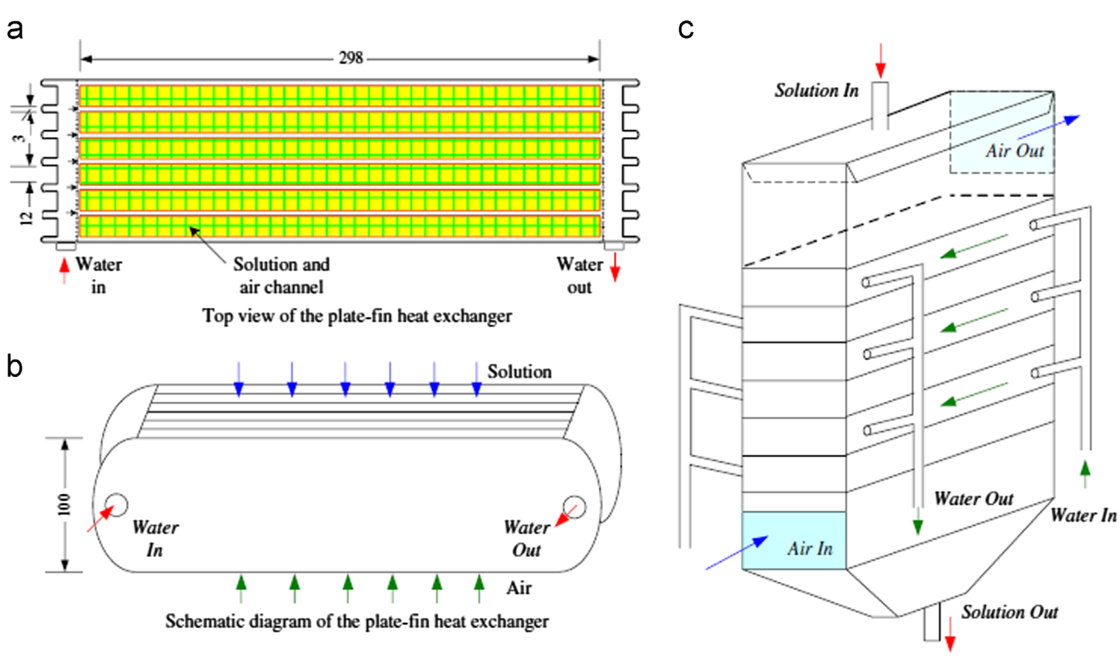


Fig. 17. Schematic diagram of internally cooled/heated dehumidifier/regenerator: [80].

the ratio of the flow rates of air to absorbent is small, whereas uniform cooling should be applied when this ratio is large [82]. A mathematical model was developed in this work to predict the performance of an absorbent dehumidifier that integrates indirect evaporative cooling to achieve an almost isothermal operation [83]. The study predicted that the thermal performance strongly depends on the physical size of the absorber, the absorbent concentration and cooling and process air mass flow rates. Liu et al. [84] showed that a decrease in the absorbent concentration is the main factor that influences the performance of an internally cooled dehumidifier, while an increase in the absorbent temperature is the main performance-restricting factor in an adiabatic dehumidifier. Internally cooled dehumidifiers have a better mass transfer performance compared with adiabatic dehumidifiers that use an external heat exchanger.

4.4. Others

Yin et al. [85] investigated an absorbent regenerator using hot air to concentrate the diluted absorbent. The aimed to utilize the wasted heat of hot air, such as the hot air from the condensers of a vapor compression refrigeration system. The results indicated that the hot air in the regenerator could be used to regenerate the absorbent when the lowest required inlet solution temperature could be met. The hot air significantly impacted the regeneration performance. Typically, a hot air temperature of approximately 65°C is recommended for systems using LiCl–H_2O as the absorbent. The dimensions of the regenerator also significantly impacted the regeneration performance. If the airflow rate is too low, increasing the length of the direction of airflow has no effect. Only when the airflow rate is high enough does increasing the length of the airflow significantly impact the regeneration performance. When regeneration processes use hot air, a sufficient absorbent flow direction height should be ensured to avoid air dehumidification in the regenerator, especially when the absorbent flow rate is relatively high.

5. Components and system design

The absorbent heat and mass exchanger is the main component of an open-cycle absorption air-conditioning system. The heat and mass transfer exchanger is responsible for reducing the air temperature and moisture content as the air passes the film or spray absorbents. In low flow systems, the absorbent dehumidifier consists of typical heat and mass transfer heat exchanger devices, thermo-storage heat and mass transfer exchanger devices and ordinary heat exchanger sorbent heat exchangers. These components are the backbone of the absorbent heat and mass transfer exchanger. Low flow heat and mass transfer devices are used for common applications in which the required air condition is high enough in humidity and low enough in latent energy. In addition, these devices are common in applications that do not require more advanced heat and mass transfer devices. Thus, these devices are common in open-cycle absorption air-conditioning systems.

5.1. Typical dehumidifier and regenerator system

Typical dehumidifier or regenerators based on spray, wetted wall (falling film) and packed bed towers are arranged in typical ways [86]. In wetted wall towers, a falling film in the plate serves as the absorbent that contacts the air. This design is ideal for applications that do not require complex air dehumidifiers, such as low thermal capacity buildings. Mesquita et al. [87] developed numerical models for simultaneous heat and mass transfer in parallel-plate dehumidifiers. Two polypropylene twin-wall plates formed the channel. Cooling water flowed inside the polypropylene plates in a cross-flow configuration with respect to the absorbent and air streams. The water mass flow rate was maintained high enough to maintain the plate walls essentially isothermal, with water temperature gains throughout the plate of less than 0.4°C. Constant thickness and the simplified model leads to an under-prediction of the dehumidification, especially for low absorbent flow rates. The numerical model can be adapted for non-isothermal conditions by introducing cooling water flow

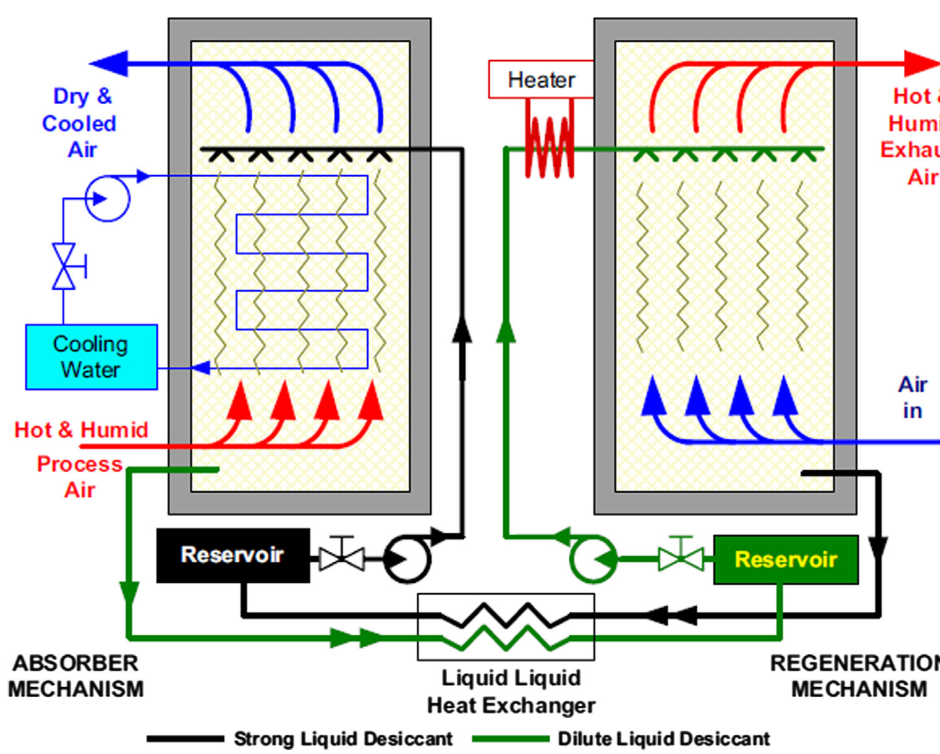


Fig. 18. Schematic diagram of the open-cycle absorption air-conditioning system either with packed bed tower, spray tower or wetted wall column [86].

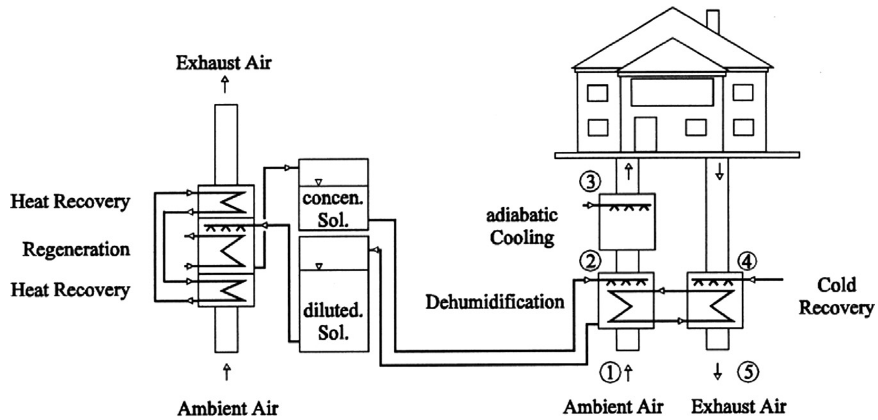


Fig. 19. Schematic diagram of the open-cycle absorption air-conditioning system with thermo-chemical storage capacity [77].

equations. Fig. 18 shows a schematic design of the absorbent dehumidifier/regenerator. In packed tower regenerators, the regeneration rate decreased as the humidity ratio of the inlet air and the concentration of the inlet solution increased [88].

5.2. Thermo-chemical storage system

Thermo-chemical storage is an option when the available source of thermal energy is not in phase with the cooling/dehumidification demand. This scenario can reduce conventional energy use. Kessling et al. [77,89] showed that hygroscopic salt absorbents, such as LiCl and $CalCl_2$, can store more than three times the energy of other adsorbents, such as zeolite and silica gel. The schematic diagram of this process is shown in Fig. 19. It shows that the high storage capacity is based on the salt concentration between the strong and diluted salt solutions. Furthermore, Miller [90] presented that the energy storage by absorbents was competitive with phase change materials, rock-bed stores and water systems. Quinnell et al. [91] showed that a combination of sensible and chemical binding energy of the absorbents yielded higher energy densities and lower thermal losses, as well as a temperature increase during discharge via an absorption heat pump.

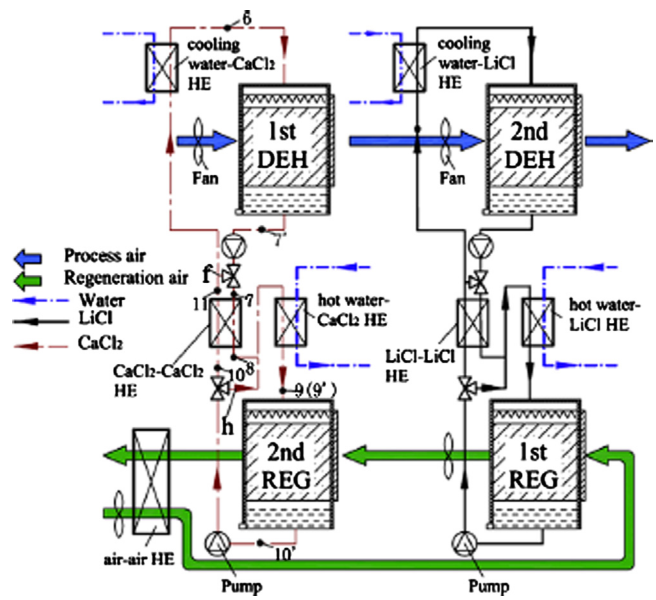


Fig. 20. Schematic diagram of the two-stage open-cycle absorption air-conditioning system [92].

5.3. Hybrid system

Hybrid installations of open-cycle absorption air-conditioning systems are used to increase the performance of the system. Two-stage open-cycle absorption air-conditioning systems that use $CaCl_2$ and LiCl have a COP and exergy efficiency of 0.73 and 23.0%, respectively, compared to the basic open-cycle absorption air-conditioning system [92]. Fig. 20 shows a multi-stage open-cycle absorption air-conditioning system. Dai et al. [93] studied multi-cycle open-cycle absorption air-conditioning systems with regard to their refrigerant cycle, absorbent cycle and cooling water cycle. Another study examined a combination of the open-cycle absorption air-conditioning system and the vapor compression system [94]. The system produced 20 to 30% more cooling power than the vapor compression system alone. Xiong et al. [92] also presented a novel open-cycle absorption air-conditioning system that used $CaCl_2$. Compared to the basic system, the thermal coefficient of performance and exergy efficiency of the system increased from 0.24 to 0.73 and from 6.8% to 23.0%, respectively. Khalid Ahmed et al. [95] presented a simulation model of a hybrid open-cycle absorption air-conditioning system. Their study showed that the system is an excellent alternative to conventional vapor absorption systems, particularly in hot and humid climates. In addition, the experimental studies of Al-Farayedhi et al. [96] show that hybrid systems work effectively in high temperature and high humidity conditions. They obtained a COP that was approximately 50% higher than that of a conventional vapor absorption system. A maximum COP of 1.25 was obtained during the study, and the unit was found to be best-suited for hot and humid areas. Fig. 21 shows a hybrid open-cycle absorption air-conditioning system combined with a vapor compression system. Kinsala et al. [98] proposed an energy-efficient air-conditioning system that used a $CaCl_2$ solution as the absorbent. Their findings indicate that the system is more efficient than a conventional A/C system. Niu et al. [99] showed that an absorbent and heat pump (LDHP) hybrid air-conditioning system provides a promising independent air dehumidification solution. They showed that a LDHP hybrid system with a double-condenser, one cooled with a solution and the other with air, is a feasible configuration to match the capacity. A novel, energy-efficient open-cycle air-conditioning system that utilizes lithium chloride (LiCl) as the absorbent has been proposed and simulated by Tu et al. [100]. Their findings show that increasing the inlet absorbent temperature in the regenerator can improve the system's performance, but this increase is also restricted by the crystallization limit of the absorbent. The appropriate mass fluxes of air in the dehumidifier and the regenerator should be accommodated to improve the performance of the open-cycle absorption system. If the

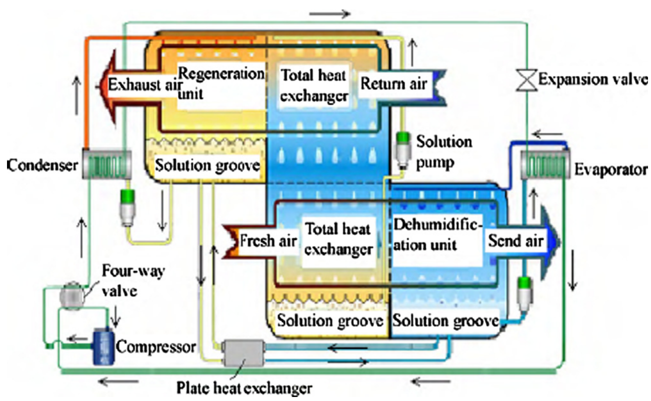


Fig. 21. Schematic diagram of the hybrid open-cycle absorption air-conditioning system with vapour compression system [97].

temperature of the supply air temperature is required to be under 20°C, the air-to-dehydrated absorbent mass flow rate ratio in the dehumidifier must be less than 2.0 [kg/kg]. When a weak absorbent is adequately regenerated, continuously increasing the mass flow rate of air into the regenerator wastes energy. The open-cycle absorption air-conditioning system is suitable for operating at wide ranges of ambient air temperature and relative humidity conditions. Yamaguchi et al. [101] studied a hybrid open-cycle air-conditioning system that consisted of a conventional absorbent system and a vapor compression heat pump. The resultant system could dehumidify 5.9 g/kg under summer conditions in Tokyo, Japan. The calculations indicate that the COPs can be increase by improving the compressor isentropic efficiency and the temperature efficiency of the absorbent heat exchanger.

Zhang et al. [102] proposed an air source heat pump in which the absorbent is used as the frost-free air source and a heat pump captures the humidity to humidify the indoor environment. Their findings indicate that frost formation is delayed due to the decreased air dew point temperature. Zhu et al. [97] showed that an absorbent-based independent humidity control (IHC) air-conditioning system driven by heat pumps can maintain the indoor temperature and humidity in the specified range. They also showed that the supply water temperature of the high-temperature refrigerator is higher than the corresponding indoor air dew point temperature, so the water would not condense on the fan coil unit (FCU) surface. In their study, the average COPs of the fresh air processor and the high-temperature refrigerator were 6.24 and 4.38, respectively, and the average COP of the whole IHC system was 5.28. Pineda and Diaz [103] showed the potential of an open-cycle absorption air-conditioning system in a refrigerated warehouse. The resultant primary fuel and CO_2 emissions savings were approximately 56% [104]. Bergero and Chiari [55] studied a hybrid air-conditioning plant obtained by combining an air dehumidification system that uses absorbent and hydrophobic membranes with an inverse cycle vapor-compression device. The percentage of saved power correlated positively with the indoor latent load and may exceed 60% at a particular set of operating conditions. In addition, the compressor of a hybrid system consumes less electricity, the system has a higher COP, and the vapor compression system is smaller due to the decreased flow rate of condensation air [93]. Rona [105] investigated a combined closed-cycle and open-cycle absorption air-conditioning system to eliminate the evaporation and cooling towers. This concept is applicable for combined air-cooling and dehumidification using thermal energy as the main source. Gari et al. [106] analyzed an integrated absorption cooling machine with a water heat-driven absorbent dehumidifier for air-conditioning systems. The integrated system has an estimated overall COP of 1.21 for a supply of hot water at 140°C fed to the generator and a cooling water supply at 30°C. This COP is 50% higher than the COP for the absorption chiller alone (0.81). The overall COP is higher than that for a double effect absorption machine if the outside air conditions and the cooling water effects are taken into consideration. Dai et al. [93] presented a hybrid system that consisted of an absorbent dehumidification, evaporative cooling and vapor compression system. The benefits of this system include a lower electric consumption of the compressor, higher COP of the system, smaller flow rate of condensation air and reduced size of the vapor compression system.

6. Building installations

Open-cycle absorption air-conditioning systems are installed in different climates: temperate, Mediterranean, Middle Eastern, and tropical climates. This distribution demonstrates that open-cycle absorption air-conditioning systems are a potential alternative to the common vapor compression air-conditioning system.

6.1. Temperate climate

An air-conditioning system was installed in an office building in Beijing, China with a total floor area of 20,000 m^2 with 10 stories [107]. During summer time, the open-cycle absorption air-conditioning system is used to control the air latent load, while the absorption chiller and compression chiller are used to control the air sensible load. This combined use of open-cycle absorption air-conditioning system and chillers increases the chilled water temperature from 15°C to 18°C. In this situation, the COP of the chiller is increased due to the increase of the evaporating temperature. The schematic design of the open-cycle absorption air-conditioning system is shown in Fig. 22. Based on the system operation, the system has an efficiency of over 80% compared to the conventional HVAC system. The thermal storage tank and the

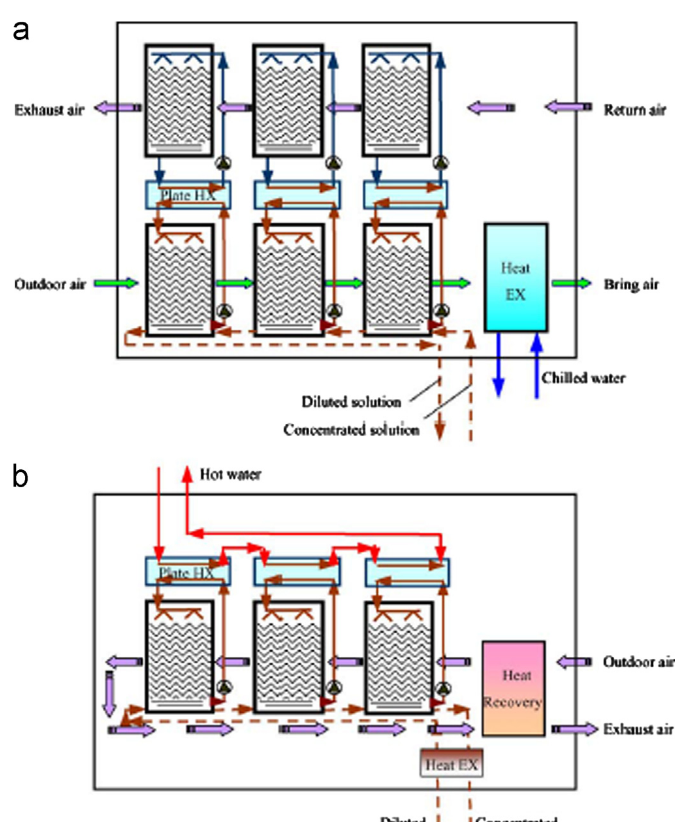


Fig. 22. Schematic of open-cycle absorption air-conditioning system with multiple air-absorbent contact exchanger (a) air dehumidifier and (b) absorbent regenerator [107].

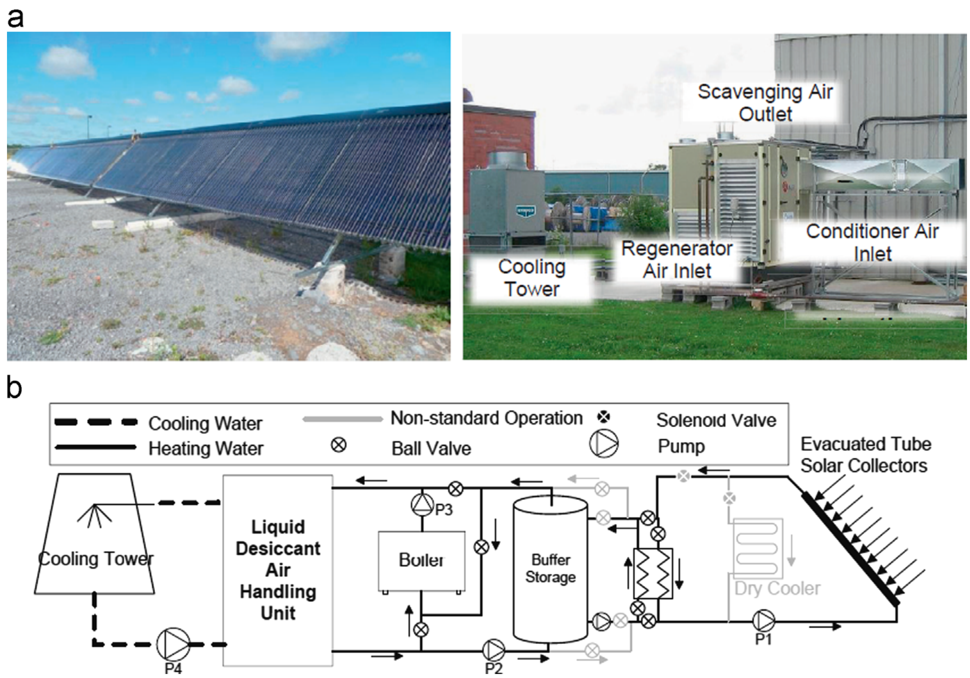


Fig. 23. Installation of the open-cycle absorption air-conditioning system in Queen University: (a) Actual view; and, (b) Schematic diagram [108].

absorbent storage tank provided long operating times due to the thermo-chemical storage capability of the absorbent.

The Queen's University Solar Liquid Desiccant Cooling Demonstration project, a solar open-cycle absorption air-conditioning system is installed at a field site in Kingston, Ontario, Canada is shown in Fig. 23 [108]. The installed system features a low-flow parallel plate open-cycle absorption air-conditioning system and a 95 m^2 evacuated tube solar collector array. While summer testing has only recently begun, five test days have shown an overall solar collector efficiency of 56%, solar fraction of 63% and a thermal COP of 0.47. The average total cooling was 12.3 kW, and the average latent cooling was 13.2 kW. The solar collector efficiency was 56%, and solar energy could provide 63% of the heat to drive the LDAC. This performance is expected to improve as the temperature and humidity increase.

Another study examined an office building with a floor space of 5700 m² in Amberg, Germany (Fig. 24) [110]. The comparatively low heating (35 kWh/m²/a) and cooling demand (30 kWh/m²/a) of the building is covered by thermally activated ceilings, assisted by appropriately conditioned ventilation air. Well water of 12-14 °C with a cooling capacity of 250 kW is used to cool the ceilings in summer. A solar driven open-cycle absorption air-conditioning system, developed by ZAE Bayern, dehumidifies the outside air with a concentrated salt solution absorbent (LiCl-H_2O) with a capacity of 70 kW. This system cools 30.000 m³/h of supply air with a capacity of 80 kW by recovering the cold from evaporative cooled exhaust air (Fig. 25). The absorbent is regenerated by solar thermal energy from a 70 m² flat plate collector array at 70 to 80°C with a maximum capacity of 40 kW. The solar energy for air conditioning is efficiently stored in approximately 10 m³ of absorbent. Summer air conditioning uses only solar energy, except from electricity for pumps and fans [110].



Fig. 24. Office building in Amberg, Germany where open-cycle absorption air-conditioning system is installed [110].

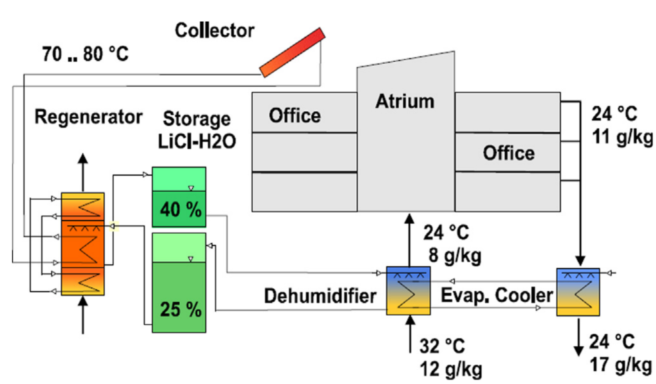


Fig. 25. Diagram of the open-cycle absorption air-conditioning system is installed [110].

6.2. Sub-temperate climate

An absorbent-based independent humidity control (IHC) air-conditioning system driven by heat pumps has also previously been presented [97]. The system consists of an absorbent fresh air processor and a high-temperature chilled water system. The operating principles of the fresh air processor and the whole system are presented in Fig. 26. The summertime performance in 2007 was investigated based on the in situ system installed in an ecological building of the Shanghai Research Institute of Building Sciences (SRIBS). Problems of microbial growth may be avoided by the elimination of wet surfaces in this system. Furthermore, an absorbent can potentially remove a number of pollutants, which will further improve the IAQ. The COP of the IHC system significantly improved by completely recovering the heat between

the fresh air and indoor exhaust air and fully utilizing the energy from the evaporator and condenser of the heat pump. The measurement results show that the indoor temperature and humidity were both in the specified range; the supply water temperature of the high-temperature refrigerator was higher than the corresponding indoor air dew point temperature, so water did not condense on the fan coil unit (FCU) surface; the average COPs of the fresh air processor and the high-temperature refrigerator were 6.24 and 4.38, respectively, and the average COP of the whole IHC system was 5.28.

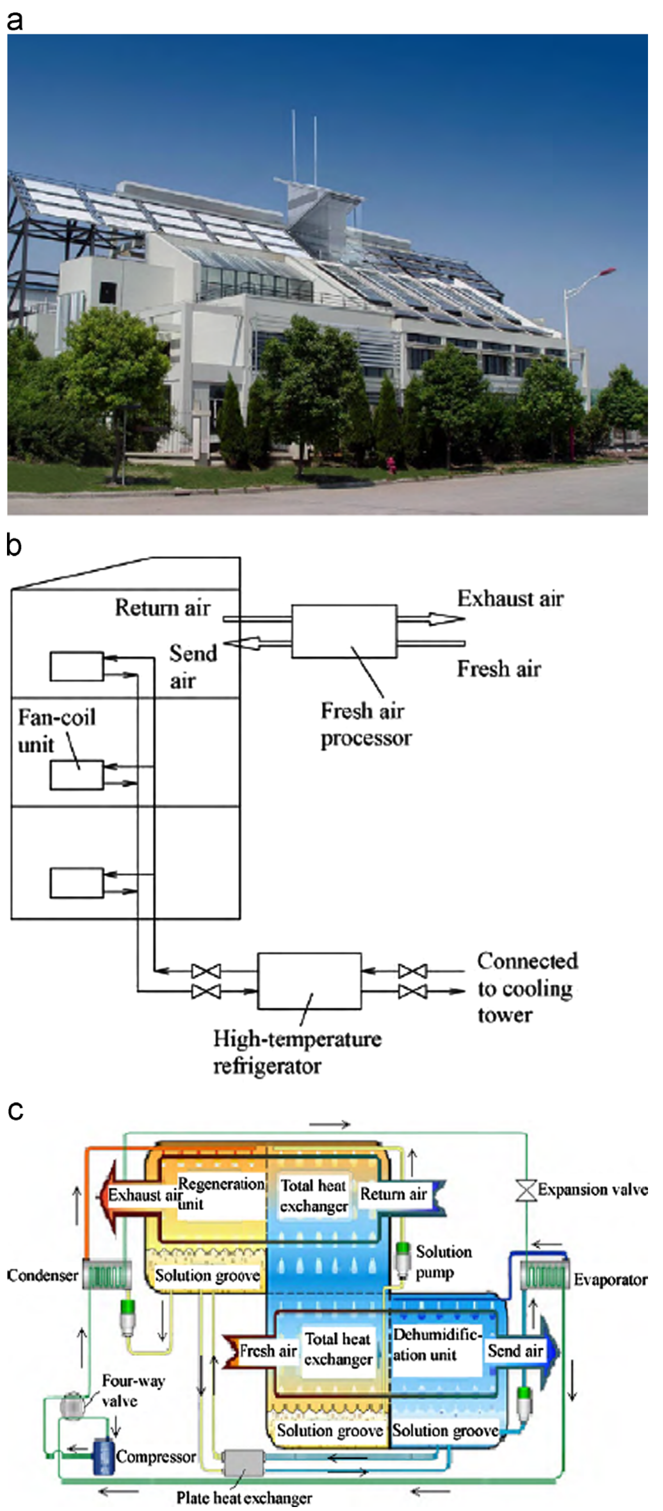


Fig. 26. Details of installed independent humidity control (IHC) air-conditioning system: (a) Shanghai Research Institute of Building Sciences (SRIBS); (b) Schematic diagram of the IHC system, and (c) Operating principle of the fresh air processor [97].

6.3. Mediterranean climate

A tri-generation plant was developed to support the air-conditioning system for a building of the Politecnico di Torino, as shown in Fig. 27 [109,111]. The layout of the system is presented in Fig. 28 and shows the internal combustion co-generator, the open-cycle absorption air-conditioning system, the cooling tower, the two heat exchangers and the connecting pipes. An economic analysis indicated that the system payback time was 6.8-7.7 years. The first plant had electrical, heating and cooling capacities of 126, 220 and 210 kW, respectively, and was characterized by an innovative internal combustion engine (ICE) that was coupled with a liquid LiCl–water open-cycle absorption air-conditioning system. The other plant had electrical, heating and cooling capacities of 100, 145, and 98 kW, respectively, and was composed of a micro-gas turbine coupled with a LiBr–water absorption chiller. From the economic point of view, a fuel tax reduction for high-efficiency cogeneration plants is an essential contribution for the support and development of these systems [112].

6.4. Middle East climate

An open-cycle absorption air-conditioning system was installed at the Energy Engineering Center at the Israel Institute of Technology (Technion) in the Mediterranean city of Haifa, as shown in Fig. 29. A schematic diagram of this system is presented in Fig. 30 [114]. The system uses solar energy for regeneration with thermal and chemical storage tanks (hot water and absorbent). The system analysis showed that the thermal COP was approximately 0.8 with a parasitic loss of approximately 10%. Based on the system analysis, the parasitic losses could be minimized by improving the overall COP. Gommed and Grossman [113] investigated a system capable of both cooling and dehumidification for air conditioning by utilizing low-grade heat. The system included a novel solution heat and mass exchanger (HME) designed to serve as the absorbent reservoir for both the absorber and desorber, which enabled the mass transfer between the two systems with minimum heat transfer losses and eliminated the need for an external recuperative heat exchanger. The use of the new HME reduced the time constant of the system, helped correct idling and stabilize control problems, and ensured a maximum absorbent concentration on the absorber side during desorber operation. The performance of



Fig. 27. Building heated and air-conditioned by the tri-generation plant in Italy [111].

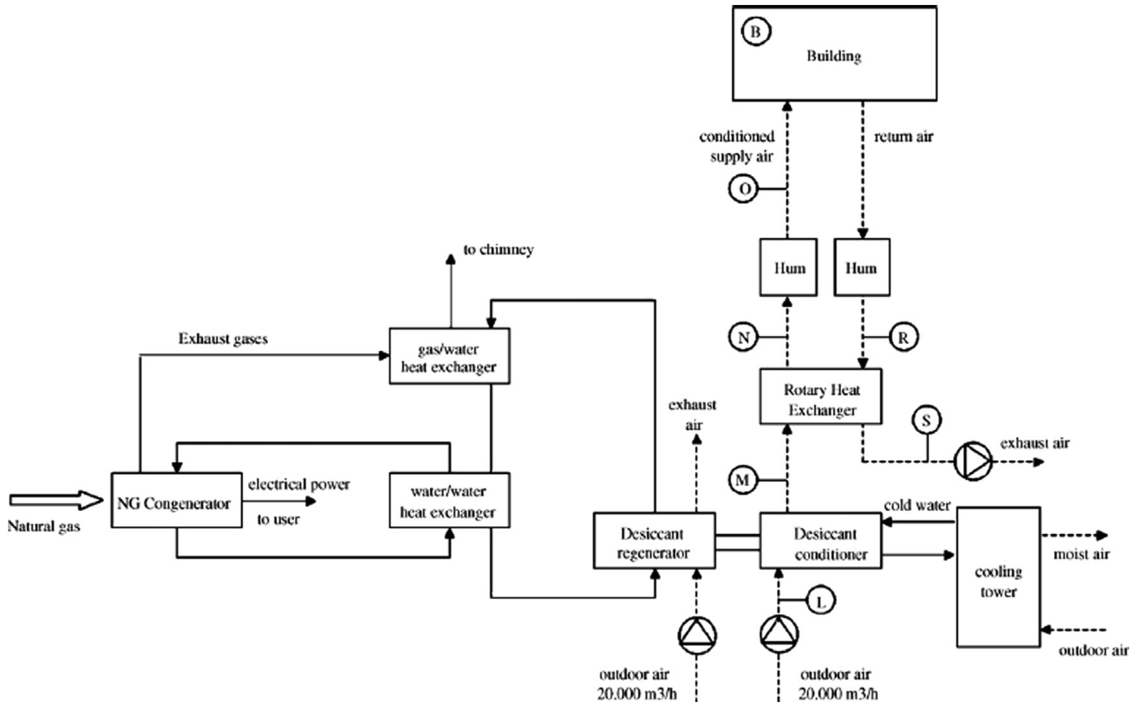


Fig. 28. Layout of the tri-generation plant in Italy [111].



Fig. 29. Actual view of the open-cycle absorption air-conditioning system showing the absorber/dehumidifier (1), desorber/regenerator (2); air ducts (3), fan (4), rotary air/air heat exchanger (5), control cabinet (6), solar collector field (7) and hot water storage tank (8) [114].

air dehumidifiers using triethylene glycol (TEG) as the absorbent under hot and humid conditions has also been investigated [115]. This study showed that the absorbent flow rate, inlet concentration and air inlet temperature were the most significant variables in predicting the moisture removal rate, whereas the absorbent flow rate, air inlet temperature and packing density were the most significant variables in predicting the column effectiveness.

6.5. Hot and humid climate

An open-cycle absorption air-conditioning system was installed at the Energy Park of the Asian Institute of Technology (AIT), Pathumthani, Thailand [116]. Fig. 31 shows a schematic diagram of the solar-regenerated absorption ventilation pre-conditioning system, and Fig. 32 shows the actual system installation. This study indicated that a solar open-cycle absorption air-conditioning system could work in a tropical climate nation such as Thailand. The humidity of outdoor air could be reduced by 11% while the temperature of the supply air was almost the same to the outdoor air. This finding indicates that an auxiliary air-cooling system is still needed to control the air temperature. In addition, Zhao et al. [117] presented an open-cycle absorption air-conditioning system installed in a 21,960 m^2 building in Shenzhen, China. This area is hot and humid. Fig. 33 shows a schematic diagram of the system installation and the hybrid open-cycle absorption air-conditioning system design. The results of this study indicated that the system could provide the required indoor thermal comfort and air quality based on the temperature, humidity and CO_2 concentration. Because the system coefficient of performance is 4.0, this system is much better than ordinary air-conditioning systems. Hence, the exhaust air is recirculated in ordinary systems to reduce air-conditioning air-cooling and dehumidification, which resulted in poor indoor air quality.

7. Applications and advantages

7.1. Indoor environment

Absorbents can treat airborne microorganisms [118]. Wang et al. [119] showed that absorbents can inactivate airborne fungi. Thus, open-cycle absorption air-conditioning systems can also mitigate serious air quality problems. Furthermore, chemical components of the air, such volatile organic compounds (VOCs), are readily absorbed by the absorbents [120]. Absorbents can sterilize the air through spraying and kill viruses, bacteria, mildew, etc. to avoid cross-contamination. Furthermore, because fresh air removes the entire latent load and some of the sensible load, fan coil units (FCUs) only operate under “dry conditions” to remove the remaining sensible load, which avoids wet surfaces in the air-conditioning system. This requirement can significantly improve the indoor air quality [121]. Therefore, these systems avoid problems caused by the recirculation of indoor air pollutants in recirculating air-conditioning systems. Furthermore, open-cycle absorption air-conditioning systems with solar-gas air conditioners could be used for heating in the winter

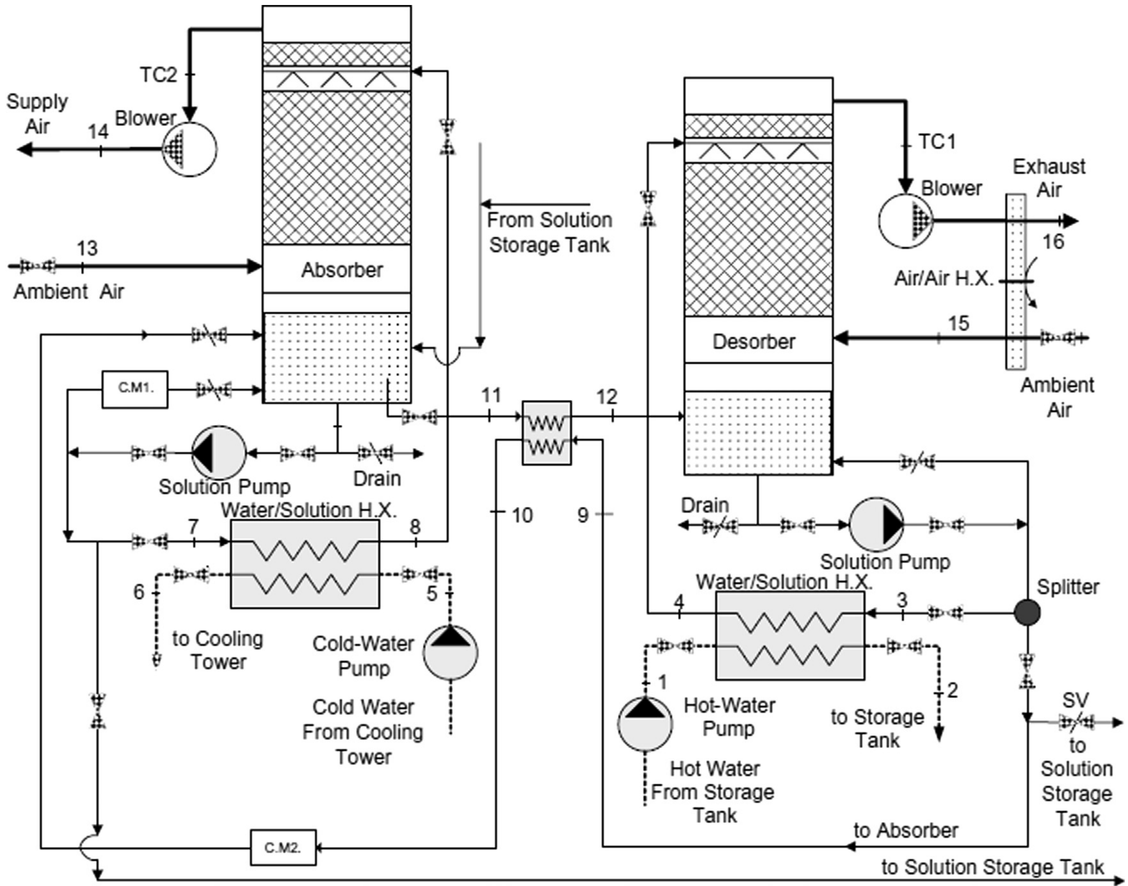


Fig. 30. Schematic description of the open-cycle absorption air-conditioning system: the solid thick lines indicate air flow; the solid thin lines indicate solution flow; the dotted thin lines indicate water flow [114].

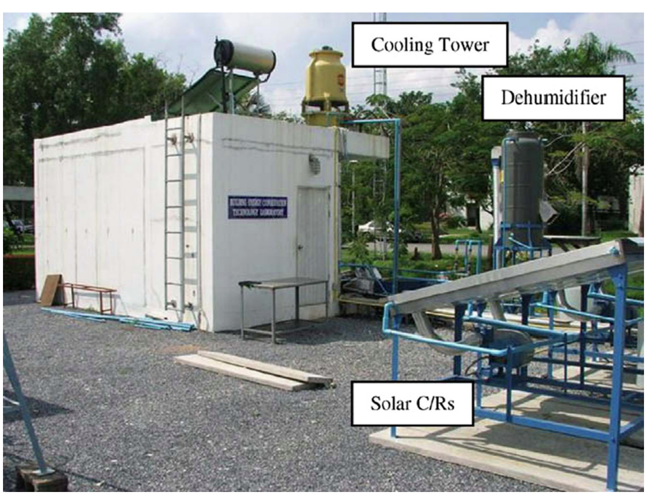


Fig. 31. The solar-regenerated open-cycle absorption air-conditioning system installed at Asian Institute of Technology (AIT) [117].

and cooling in the summer. Previous studies have determined that the conditioner performance could be enhanced by using a gas-powered regenerator when the available solar insolation is insufficient. Using a portion of the return air to cool the conditioned space would make the system more cost effective [122]. In Beijing, China, open-cycle absorption air-conditioning systems handle outdoor air to remove the entire latent load and part of the sensible load of the building, and indoor terminal devices (FCU or radiant ceiling) handle the remaining sensible heat throughout the year. In the summer, chilled water is not required to remove the latent load, so the temperature of the chilled water can be increased to 15–18°C, which leads to higher evaporating temperatures and a higher COP of the refrigerator. In winter, the air is easily humidified by increasing the temperature of the absorbent, and no extra humidifying devices are required in the IHC system [123]. Wu [124] attempted to improve the indoor air quality by using a packed-bed absorber containing triethylene glycol (TEG) to remove volatile organic compounds (VOCs). Generally speaking, a higher concentration in the TEG solution resulted in lower equilibrium concentrations of VOCs in the gas phase. Thus, VOCs were easily absorbed by higher concentration TEG solutions. Therefore, the mass transfer performance was better for higher concentration absorbents.

7.2. Energy savings

Niu et al. [125] showed that the power savings of an open-cycle absorption air-conditioning system would be even greater if alternate low-grade heat resources were available, such as industrial waste heat and solar energy. Tu et al. [100] showed that open-cycle absorption air-conditioning systems are suitable for operations over wide ranges of ambient air temperature and relative humidity conditions. However, Wang et al. [126] showed that an ideal open-cycle absorption air-conditioning system is not always better than a condensation-based dehumidification system in certain conditions. The exergy efficiency of the ideal system will be lower than that of condensation-based dehumidification systems if the dehumidification temperature is higher than 36 °C. Li and Zhang [127] showed that the heat provided for regeneration will be unfavorable to the dehumidification process when the humidity of the surrounding atmosphere is of high. In this case, electrodialysis can be used in the membrane regeneration process with a solar photovoltaic generator. Yin and Zhang [128]

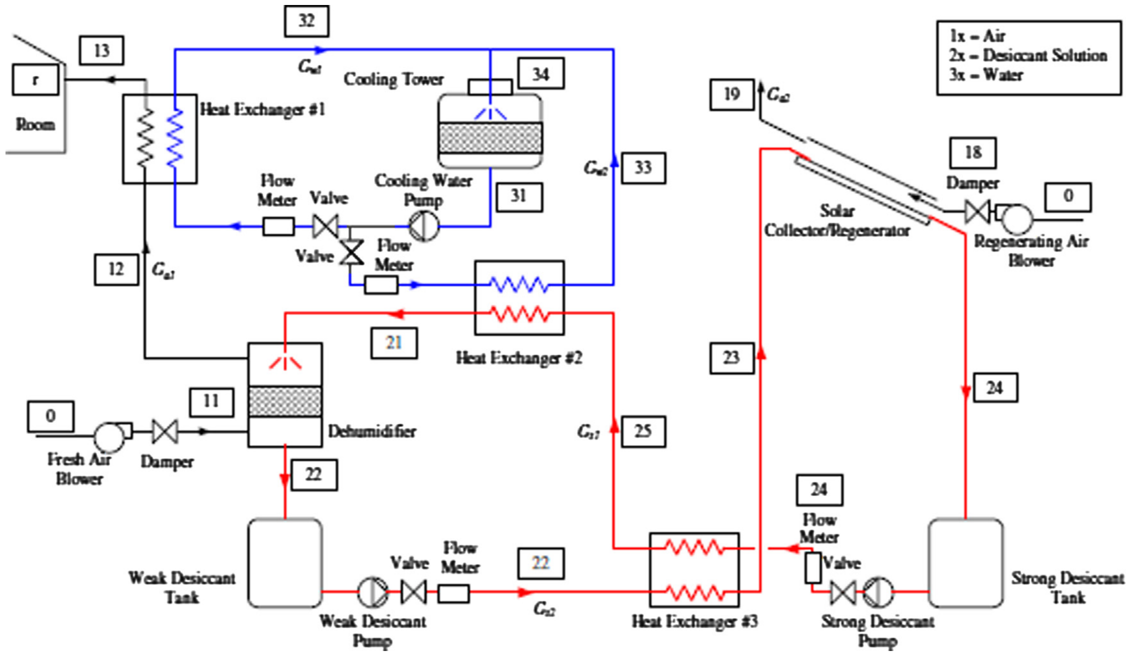


Fig. 32. Schematic of the solar-regenerated open-cycle absorption air-conditioning system installed at Asian Institute of Technology (AIT) [117].

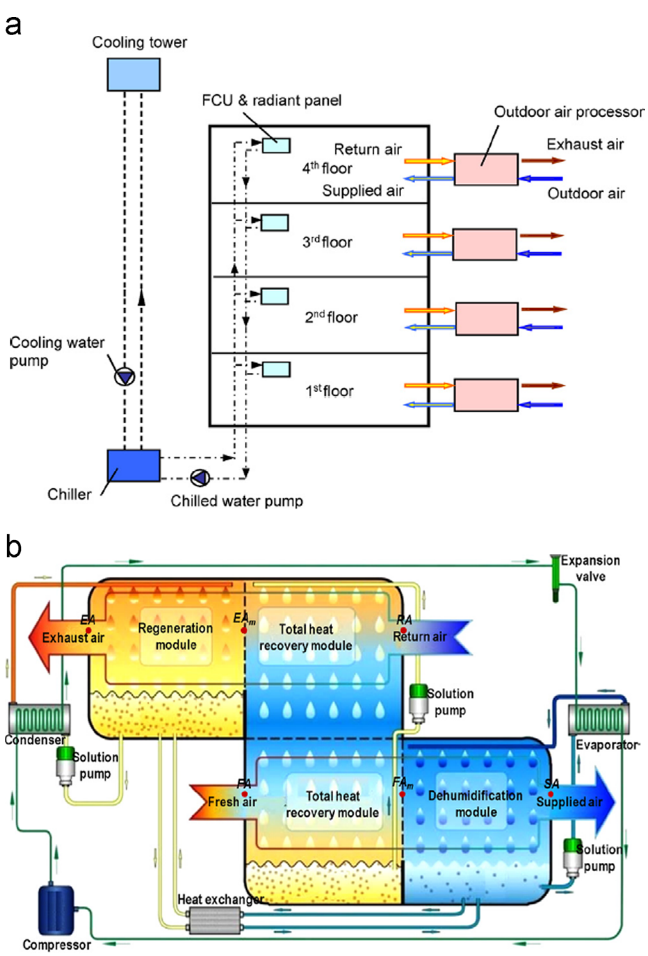


Fig. 33. Schematic of the hybrid open-cycle absorption air-conditioning system installed at office building in Shenzhen, China: (a) Installation of the system in multi-story building, and; (b) Diagram of the open-cycle absorption air-conditioning system [118].

showed that an internally heated regenerator not only increases the regeneration rate but also exhibits a higher energy utilization efficiency. Bassuoni [129] showed that the payback period of the absorbent dehumidification system is 11 months with an annual running cost savings of approximately 31.24% compared with vapor compression system dehumidification. Feyka and Vafai [130] showed that open-cycle absorption air-conditioning systems are well suited for tropical climates with small diurnal temperatures swings and relatively high humidity, even though they are ineffective for required temperature reductions above 20°C. Compared to a conventional air-conditioning system with primary return air, an open-cycle absorption air-conditioning system consumes notably less power. The maximum power saving ratio is 58.9% when the fresh air ratio is 20%, and the minimum ratio is 4.6% when the fresh air ratio is 100% [125].

7.3. Others

Many avenues are available for the further research and development of absorbent-based air-conditioning systems. Li et al. [131] proposed a new photovoltaic-electrodialysis (PV-ED) regeneration method for an open-cycle absorption air-conditioning system. The new method utilizes electrodialysis technology to regenerate absorbent and solar photovoltaic technology for the energy supply. Because the PV-ED method can efficiently concentrate the absorbent, additional theoretical and experimental work is necessary to improve the design of such a regeneration system not only for open-cycle absorption air-conditioning system but also for other absorption refrigeration systems. In addition, this new method is stable and withstands the adverse impacts of high humidity; its performance is much higher than that of thermal regeneration systems while avoiding the low efficiency of the photovoltaic system. In addition, purified water can be obtained as part of the regeneration process [127].

Reverse osmosis can also be used to regenerate absorbents [68]. This system is very attractive for countries such as Saudi Arabia [17]. The combined production of cooled air and fresh water is another application of open-cycle absorption air-conditioning systems [132]. Audah et al. [132] studied the feasibility of using a solar-powered open-cycle absorption air-conditioning system to

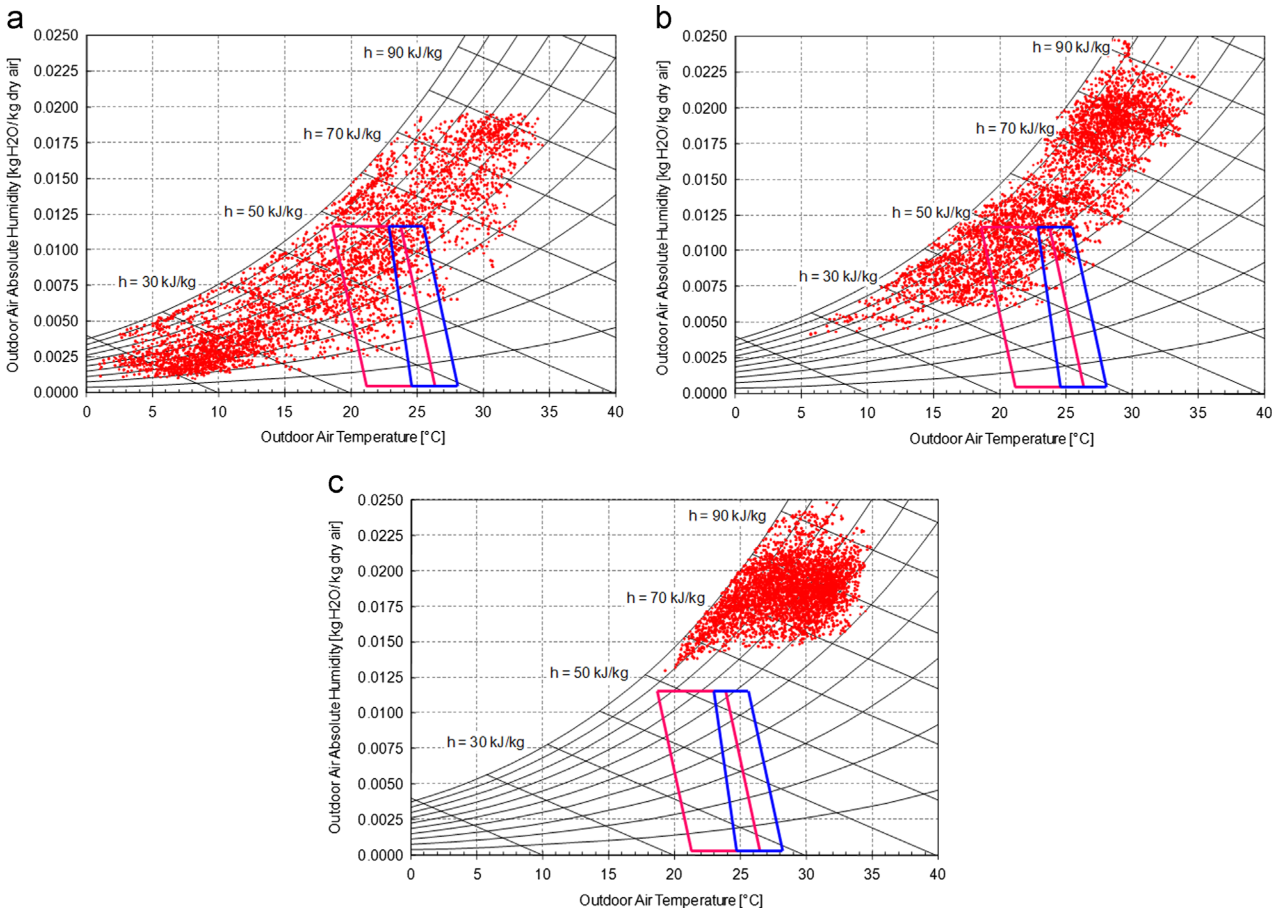


Fig. 34. Different outdoor air conditions for different climates: (a) Tokyo, Japan for temperate climate; (b) Hong Kong, SAR China, for Subtropical/Subtemperate climate, and; (c) Jakarta, Indonesia for torpical climate. Pink block represent acceptable temperature and humidity during cold and dry outdoor conditions and blue block represent acceptable temperature and humidity during hot and humid outdoor conditions based on ASHRAE Standard 55-2004 [33].

meet both a building's cooling and fresh water needs in the humid climate of Beirut. The proposed system was shown to save energy, produce water, and create a comfortable environment using renewable energy sources without harm to the environment because water was extracted from the atmosphere. A district heating and cooling system for a zero-energy community (ZEC) distributes the hot absorbent for absorbent-based HVAC systems in each home and incorporates local storage [133]. Such an absorption-based district system shows benefits compared to a conventional district system that uses heated/cooled fluids.

Absorbents can also be used to dry grain, which still predicted to be economically unfeasible [134]. Nevertheless, Pietruschka et al. [72] showed that an open-cycle absorption air-conditioning system dryer has a higher energy efficiency compared to the conventional hot air-based drying systems used in industrial and agricultural sectors. Barati et al. [135] studied the drying of gelcast parts by the absorbent method. This method avoids the defects generated during conventional drying, and the drying time was reduced 10-fold. Rane et al. [104] showed that absorbent-based dryers are more efficient than conventional hot air-based drying systems used in industrial and agricultural sectors. Their experiments demonstrated that the specific moisture extraction rate (SMER) improved considerably compared to conventional drying methods. The peak SMER obtained during the drying cycle was 1.86 kg/kWh of heat. The average SMER of absorbent-based dryers was 1.5 kg/kWh of heat input compared to 0.66 kg/kWh of heat for the hot air-based dryer for similar application. Absorbent-based dryers are more energy efficient than conventional hot air-based

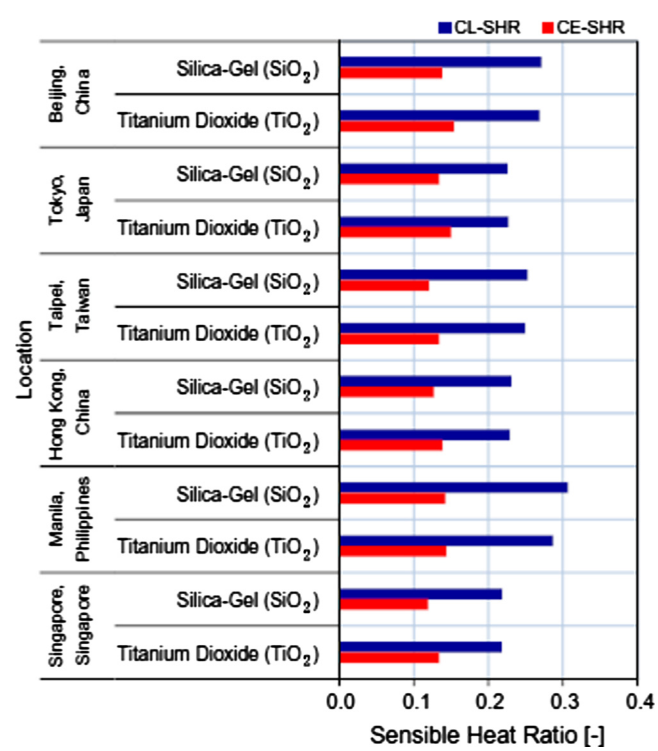


Fig. 35. Sensible Heat Ratios (SHR) for different cities in East Asia [10].

drying systems used in industrial and agricultural sectors. Lychnos et al. [136] presented a study in which they directly measured the properties of concentrated seawater brines produced via a solar evaporation salt plant. Their findings indicate that the seawater was sufficiently hygroscopic for use in absorbent cooling cycles that could cool air to 8.0–10.9°C below the ambient temperature. In comparison, simple evaporative cooling only reduced the temperature by 3.8–8.7 °C. Absorbent cooling can extend the growing seasons of greenhouse crops, thus providing an adaptive measure against climate change. Lychnos and Davies [137] used a validated computer model to predict the performance of the whole system during the hot summer months in Mumbai, Chittagong, Muscat, Messina and Havana by considering examples temperate, sub-tropical, tropical and heat-tolerant tropical crops (lettuce, soybean, tomato and cucumber, respectively). Compared to conventional evaporative cooling, the absorbent-based system lowered the average daily maximum temperatures in the hot season by 5.5 to 7.5°C, which was sufficient to maintain viable growing conditions for lettuce throughout the year. Tomatoes, cucumbers and soybeans could be optimally cultivated through most summer months using this system. Thus, open-cycle absorption air-conditioning systems can be applied in any field where air dehumidification and purification is needed with available sources of cheaper thermal energy.

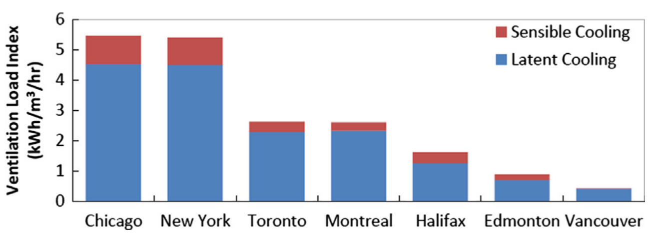


Fig. 36. Latent and sensible Ventilation Load Index (VLI) for several cities with a set point of 24C and 50% relative humidity [108].

8. Situation and solution

In some tropical countries, almost one third of the electricity is consumed by air conditioning, which is necessary throughout the year due to prevailing high ambient temperatures. Thus, reduction of electricity consumption is a pressing need for consumers, and the cessation or reduction of capacity expansion is a pressing need for suppliers of power. Because conventional systems are energy intensive, more energy efficient systems need to be developed [138]. Fig. 34 shows the different outdoor air conditions in different climates: temperate, subtropical/subtemperate and tropical climates. Furthermore, the sensible heat ratios (SHRs) for different east Asian climates to maintain the indoor thermal environment consist mainly of latent loads or dehumidification (Fig. 35). These temperatures indicate that air-conditioning is necessary to support the indoor environmental conditions in a tropical climate to maintain the indoor environmental comfort, as shown in Fig. 3. In addition, because the total cooling load is dominated by latent cooling or air dehumidification even in temperate climate (See Fig. 36), using absorbents as the dehumidifier is an advantage to maintain the indoor thermal and air quality level (Table 2), which also simultaneously maintains the air quality. Table 3 shows the benefits of using absorbents to dehumidify the air. Thus, systems that separately handle latent air and sensible loads are more efficient, cheaper, and permit the introduction of air conditioning systems to countries where they are not widespread. Furthermore, decreasing the size and costs of new systems will increase the competitiveness of the air conditioning industry [13]. Domestic air conditioning equipment is mainly based on vapor compression cycles,

Table 2
Applications characteristic that favor sorbent dehumidification [139].

Characteristic	Cause	Building Application
Ratio of Latent Load to Total Cooling Load > 30%	• High Occupancy • High Level of Outdoor Air • High Internal Latent Loads from Processes	• Movie Theaters • Schools • Stores • Restaurants • Meeting Halls • Ice Skating Rink
Dry Air Requirements	• Air Space Specifications for Processes	• Laboratories • Computer Rooms • Libraries • Museums • Munitions Storage • Avionics Repair
High Outside Air Requirements	• ASHRAE Standard 62 (15 cfm per person)	• Movie Theaters • Schools • Stores • Restaurants • Meeting Halls • Hospitals • Offices
High Electric Rates	• Increased Utility Demand During Hot Summer Days	• Not Application Specific
Indoor Air Quality Problems	• Outdoor Air Requirements • High Level of Airborne • Infectious Agents • High Levels of Indoor CO_2	• Schools • Dormitories • Hospitals • Meeting Halls • Offices

which significantly increases the peak electric power demand in the summer and can often result in reaching the capacity limit of the network, risking blackouts. Hybrid tri-generation and solar cooling plants can decrease the electricity consumption by exploiting the simultaneity of cooling demand and maximum solar radiation [140].

According to Fu et al. [141], combined cooling, heating and power (CCHP) systems can significantly increase the efficiency of fuel use by generating electricity onsite and recycling the exhaust gas for heating, cooling, or dehumidifying. A challenge for CCHP systems is the efficient integration of distributed generation (DG) equipment with thermally activated (TA) technologies. The waste heat from the jacket water is used to drive the absorption dehumidification systems and thus separately control the heat and humidity. Gasparella et al. [142] attempted to synergize this process by combining an underground thermal energy storage (UTES) system with an absorbent-based air-handling unit (AHU). The D&GSHP saved approximately 30% of the primary energy per year with respect to a conventional HVAC system that uses gas-fired water heaters for heating and electric compression chillers for cooling. Although the savings of a GSHP system are approximately 26.6% to begin with, the D&GSHP system is smaller because its components are smaller. According to economic reports, the payback period decreases more than 14 years for the GSHP system to less than 8 years for the D&GSHP, compared with the conventional plant solution. Furthermore, Grossman [143] stated that bulk of closed-cycle absorption air-conditioning system research has been focused on increasing the operating temperature to improve the efficiency via multi-staging, open-cycle absorption air-conditioning systems. Such systems have been developed for use with low temperature heat sources, such as flat plate solar collectors. In both of these systems, the economics of solar cooling are dominated by the solar part of the system (collectors and storage).

In general, many studies have demonstrated the advantages of absorbent-based air-conditioning systems, compared to existing systems, for controlling both the air thermal, biological and chemical contents and the advantages of coupling these systems with different and existing systems to form hybrid systems. Hence, absorbent-based air handling systems are a potential alternative to typical air handling systems. These absorbent-based systems are cheaper, smaller, and simpler to maintain. Furthermore, they can be operated using alternative energy sources. Therefore, further research and studies are needed to address the above issues and simultaneously educate the public (ordinary users) and developing countries about the benefits and advantages of using absorbent-based air-conditioning systems as an alternative to widely established systems.

Table 3
Benefits of dehumidification using sorbents [139].

Increased Comfort	Indpendent Control of Humidity and Temperature • Sorbent Unit Control's Humidity • Conventional Cooling System Controls Temperature
Lower Operating Costs	• Utilize Lower Cost Natural Gas for Regeneration • Conventional Cooling System Operates at a Higher • Efficiency Due to Higher Suction Temperatures
Lower Peak Electric Demand	Switch Latent Cooling to Alternative Energy Sources • Natural Gas • Steam • Heat Recovery
Heat Recovery Options	Heat Recovery Sources • Engine Driven Chillers • Cogenerators • Condenser Heat • Steam Condensate
Dry Duct Systems	High Humidity Air and Dust in Ducting Results in • Fungus Growth • Bacteria Growth
ASHRAE 62-89	Reduced Indoor Air Quality The Standard Addresses Increased Levels of Outdoor Air • Increase Total Cooling Load • Increase Latent Load
CFC Free **Improved Indoor**	Sorbent Systems Can Directly Address this Problem Sorbent Systems Do Not Use CFC's fro Moisture Removal • Approriate Levels of Fresh Air
Air Quality	• Reduced Levels of Air Borne Bacteria • Air Treatment Chemical With Absorbents
Reduced Building Maintenance	Reduced Building Maintenance Activities Associated with High Humidity Levels • Mold and Mildew Remediation • Corrosion • Replacement of Wall Coverings • Replacement of Window Coverings • Replacement of Carpeting

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